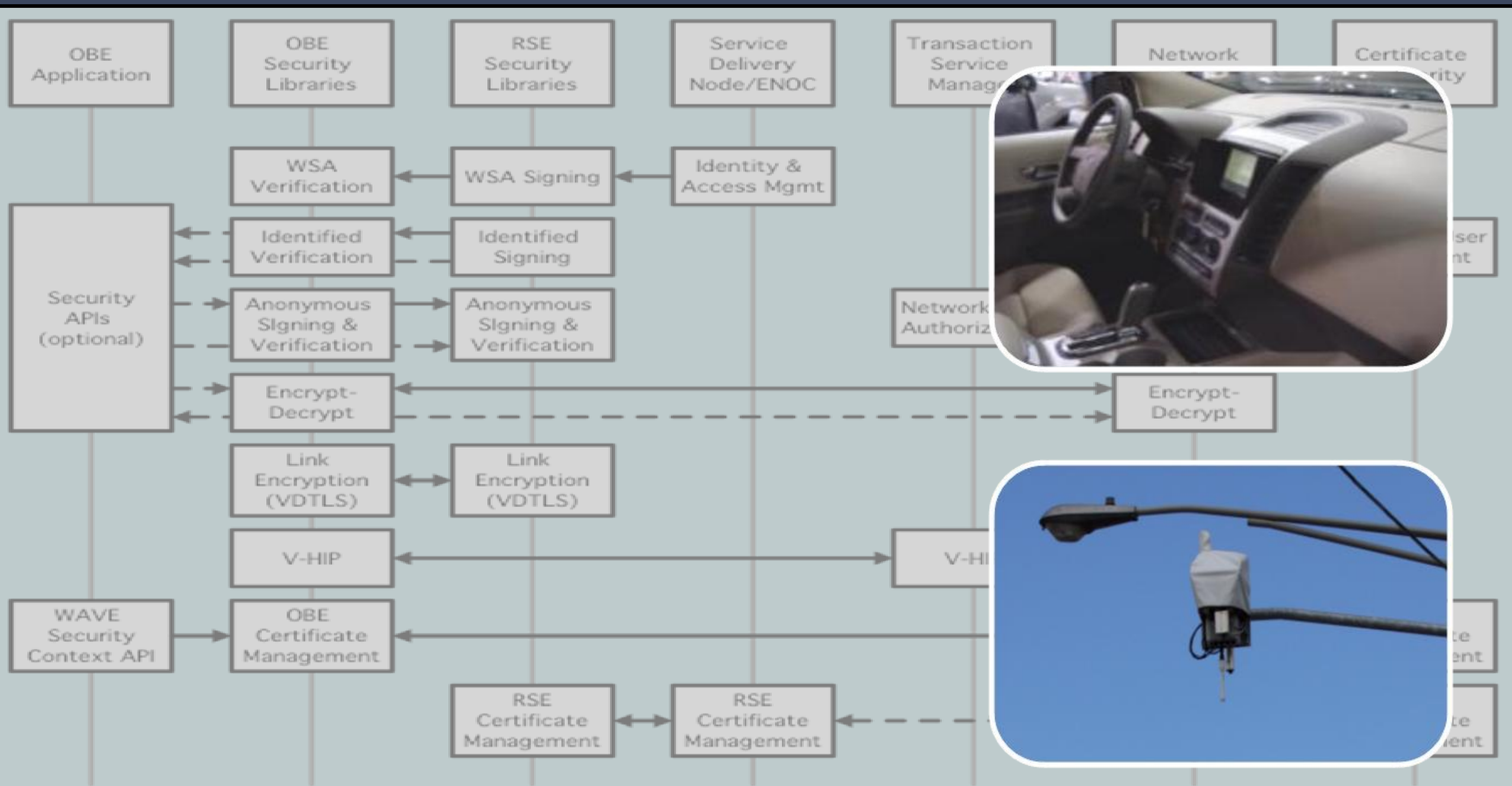
Final Report:

Vehicle Infrastructure Integration Proof of Concept Results and Findings Summary – Vehicle



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Notice 1

This material is based upon work supported by the United States Department of Transportation under Cooperative Agreement # DTFH61-05-H-00003.

Notice 2

This report includes references to "Vehicle Infrastructure Integration" (VII). This program name was in official use at the inception of and during the execution of the work described in this report. The United States Department of Transportation has initiated a new program entitled "IntelliDrive^{SM}" which now encompasses all activities that were previously part of VII.

Notice 3

Notice 4

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16. Abstract

This document describes the objectives and the approach to the testing of the VII Proof of Concept system. A summary of the test results and findings for both the major system functions and the applications designed for the system, are presented along with recommendations for system improvements.

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GLOSSARY OF TERMS AND ACRONYMS

3G	Third Generation Cellular (Wireless Data System)
AASHTO	American Association of State Highway and Transportation Officials
AOCA	Anonymous OBE Certifying Authority
AMDS	Advisory Message Delivery Service
API	Application Programming Interface
BAH	Booz Allen Hamilton
BER	Burst Error Rate
BMW	BMW of North America, LLC
BSP	Board Support Package
CA	Certificate Authority
CAN	Controller Area Network
CCL	Channel Coordination Layer
CCH	Control Channel
CEP	Circular Error Probable
CM	Certificate Manager
COTS	Commercial Off-the-Shelf
CPU	Central Processing Unit
CRL	Certificate Revocation List
DGPS	Differential Global Positioning System
DSRC	Dedicated Short Range Communications
DTE	Development Test Environment
ECC	Elliptic Curve Cryptography
ENOC	Enterprise Network Operations Center
ESB	Enterprise Service Bus
XML	Extensible Markup Language
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
FPGA	Field Programmable Gate Array
Gbps	Gigabit Per Second
GHz	Giga-Hertz
GID	Geographic Intersection Description
GM	General Motors Corporation
GPS	Global Positioning System
HANDGPS	High Accuracy National Differential GPS
HB	Heartbeat
HIP	Host Identity Protocol
HMI	Human Machine Interface
HPSAM	High Performance Security Accelerating Module
HTTP	Hypertext Transfer Protocol
ILS	Information Lookup Service
IP	Internet Protocol
IPv4	Internet Protocol Version 4
IPv6	Internet Protocol Version 6
ISO	International Standards Organization
IVI	Intelligent Vehicle Initiative
I2V	Infrastructure to Vehicle

IVPS	In-Vehicle Payment Service
IVTP	In-Vehicle Toll Processing
ITS	Intelligent Transportation Systems
JMS	Java Message Service
JVM	Java Virtual Machine
LIN	Local Interconnect Network
LLCF	Low Level CAN Framework
LTP	Local Transaction Processor
LTTP	LTP Toll Processing
MAC	Medium Access Control
MDOT	Michigan Department of Transportation
MEDS	Map Element Distribution System
MEG	Map Element Generator
MHz	Mega-Hertz
MINAP	Michigan Network Access Point
MTU	Maximum Transmission Unit
NTPDA	Network Trip Path Data Accumulator
NUC	Network User Component
NUG	Network User Gateway
NUPS	Network Users Payment Service
OAA	OBE Authorizing Authority
OBE	On-Board Equipment
OCM	OBE Communications Manager
OEM	Original Equipment Manufacturer
OBNA	Off-Board Navigation Application
OS	Operating System
OSGi	Open Services Gateway Initiative
PC	Personal Computer
PCI	Peripheral Component Interconnect
PDC	Probe Data Collection
PDCS	Probe Data Collection Service
PDDS	Probe Data Distribution Service
PDSS	Probe Data Subscription Service
PDM	Probe Data Management
PDU	Protocol Data Units
PDS	Probe Data Service
PDVC	Probe Data Vehicle Component
PER	Packer Error Rate
PKI	Public Key Infrastructure
POC	Proof of Concept
PSC	Provider Service Context
PSID	Provider Service Identifier
PSN	Probe Sequence Number
RCOC	Road Commission for Oakland County
RF	Radio Frequency
RITA	Research and Innovative Technology Administration
RSE	Roadside Equipment
SAE	Society of Automotive Engineers
SCH	Service Channel

SDN	Service Delivery Node
SDRAM	Synchronous Dynamic Random Access Memory
SIT (Tunnel)	Simple Internet Transition (Tunnel)
SOA	Service Oriented Architecture
SOAP	Simple Object Access Protocol
SPAT	Signal Phase and Timing
SRS	Software Requirement Specification
TCP/IP	Transmission Control Protocol/ Internet Protocol
TMT	Technical Management Team
TPGA	Trip-Path General Application
TPT	Trip-Path Transmission
TSM	Transaction Service Manager
UDP	Universal Datagram Protocol
URL	Uniform Resource Locator
USDOT	United States Department of Transportation
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
VAPI	Vehicle Application Programming Interface
V-DTLS	VII-Datagram Transport Layer Security
VEG	Vehicle Expert Group
V-HIP	VII-Host Identity Protocol
VGA	Video Graphics Array
VIDMT	Vehicle Interface Device Management Tree
VII	Vehicle Infrastructure Integration
VIIC	Vehicle Infrastructure Integration Consortium
VIN	Vehicle Identification Number
VIS	Vehicle Interface Service
VPN	Virtual Private Network
VSC	Vehicle Signage Component
VW	Volkswagen of America
WAAS	Wide Area Augmentation System
WAVE	Wireless Access in Vehicular Environments
WME	Wave Management Entity
WO	Work Order
WSA	WAVE Service Advertisement
WSC	WAVE Security Context
WSMP	WAVE Short Message Protocol

1 Abstract

This document describes the objectives and the approach to the testing of the Vehicle Infrastructure Integration (VII) Proof of Concept (POC) system. A summary of the test results and findings for both the major system functions and the applications designed for the system, are presented along with recommendations for system improvements.

2 Organization of the Final Report

The VII Cooperative Agreement Program final report is organized into five volumes:

Volume 1a--Final Report: VII Proof of Concept Executive Summary – Vehicle
This volume provides an overview of the program goals and objectives, program organization, program technical direction and the key findings and recommendations. The report does not detail test results. This report is recommended for executives and managers of VII communities concerned with the deployment of VII systems.

Volume 2a -- Final Report: VII Proof of Concept Technical Description – Vehicle
This volume describes the technical approach of the program and specifically describes the VII POC system architecture, the system component design and the sample applications designed to enable some of the system testing. In addition the deployment of the system to the test track and development test environment is described. This report is recommended for engineering managers and practicing engineers concerned with the deployment of VII systems.

Volume 3a--Final Report: VII Proof of Concept Results and Findings Summary – Vehicle
This volume describes the test objectives and approach and presents a summary of results and findings for both the system testing and the application testing. Detailed results are not presented. This report is recommended for engineering managers and engineers concerned with the deployment of VII systems. It assumes the reader has knowledge of the VII POC system architecture as described in Volume 2a.

Volume 4a -- Final Report: VII Proof of Concept System Detailed Test Results – Vehicle
This volume describes the system test objectives, the system test approach and details the results of the individual components and the end-to-end system tests. This report is recommended for engineers concerned with the deployment of VII systems. It assumes the reader has knowledge of the VII POC system architecture and components as described in Volume 2a.

Volume 5a-- Final Report: VII Proof of Concept Application Detailed Test Results – Vehicle
This volume describes application test objectives, the application test approach and details the results of the individual application tests. This report is recommended for engineers concerned with the deployment of VII systems and the design VII applications. It assumes the reader has knowledge of the VII POC system architecture and applications as described in Volume 2a.

Volumes 1a, 2a and 3a have complimentary reports: Volumes 1b, 2b and 3b which describe the development and testing of the POC Infrastructure written by Booz Allen Hamilton (BAH).

3 VII POC Program Overview

3.1 Background

During the 10th World Congress held in Madrid, Spain (November 2003), the United States Department of Transportation (USDOT) announced a new initiative, namely, VII. This initiative represents the confluence of three areas of high interest to transportation policy managers: the Intelligent Vehicle Initiative (IVI), an emphasis on improved traffic operations, and the continuing evolution in telecommunication technology.

Regarding the latter item, the Federal Communications Commission (FCC) has allocated 75 MHz at 5.9 GHz for the primary purpose of improving transportation safety. In addition to safety of life and public safety applications, the FCC's Final Report and Order also allows private and non-safety applications to make use of the spectrum on a lower priority basis. Dedicated Short Range Communications (DSRC), the wireless medium, will allow vehicles to communicate with a low-cost roadside infrastructure, as well as with each other, in real time. This communications capability, in combination with a nationwide data collection and processing network, will facilitate improvements to safety, mobility and productivity/convenience.

Reducing the number and severity of roadway transportation incidents is a top priority of the USDOT. Development of a system supporting communication between vehicles and between vehicles and a roadway infrastructure has the potential for positively contributing to the government's goal of improving transportation safety. Such real-time communications would enable a range of crash avoidance and crash mitigation applications with the potential to reduce traffic deaths and injuries, while simultaneously enabling a host of additional applications with secondary benefits, such as optimized traffic and incident management systems.

To enable this vision, it was proposed to undertake a project to specify, design, build and test a small-scale instantiation of the envisioned national system to determine if the concept was sound and could support the intended use. Pending the anticipated results of the system's testing, a nationwide system was would be deployed. It was understood that the success of the project required close collaboration between the USDOT, the State Departments of Transportation through the American Association of State Highway and Transportation Officials (AASHTO), and light-duty vehicle manufacturers. These primary stakeholders were brought together by the USDOT in the National Vehicle Infrastructure Integration Coalition.

3.2 Program Goals and Objectives

The original program goals included development and testing of a concept system that could be nationally deployed beginning some time around 2010, that would provide a mechanism for wirelessly sending and receiving roadway information to and from vehicles, and between vehicles to satisfy the following viability criteria*:

Safety

- Provides for infrastructure-initiated safety applications.
- Supports vehicle-initiated safety applications.

Mobility

- Provides for collection of various data from vehicles.
- Provides for use of collected mobility data by state and local authorities.

- Exhibits sufficient benefit in terms of road and traffic management and transportation efficiency.

Private Services
- Vehicles can access private services through the system.
- Private services can access vehicles through the system.
- Co-existence of private services with safety and mobility services is economically viable.
- Private services can be implemented in a manner that does not interfere with Safety and Mobility Applications.

Security
- System is resistant to denial of service, replay and intrusion attacks.
- Security compromises can be identified and mitigated.
- Security credentials can be properly distributed and managed at all levels of deployment.

Maintainability
- Roadside Equipment (RSE) software can be remotely managed through the network.
- VII-related vehicle software can be securely maintained over the vehicle life cycle.

Privacy
- Cannot track an individual vehicle over any road segment longer than 2 km.
- Cannot identify any individual vehicle as violating a traffic law through publicly collected data.
- Cannot identify a vehicle or a vehicle occupant or owner from messages sent to, or through, the infrastructure.

*Note: These criteria were developed by the Vehicle Infrastructure Integration Consortium (VIIC) at the start of the program. They were agreed upon between VIIC members and the USDOT. Other criteria have been proposed, but as of this date, none have been fully agreed upon by all of the VII stakeholders. The other criteria are generally a simplified and less comprehensive set relative to the criteria presented here. These criteria are used for completeness, and in general, any differences between this set and the others that have been discussed are minor.

3.3 Project Roles and Responsibilities

The system concept was understood to consist of a roadside network component and an on-board vehicle equipment component. The responsibility for the network and RSE was assigned to BAH, a USDOT contractor and the On-Board Equipment (OBE) to light-duty vehicle manufacturers, represented by the VIIC. Additionally, it was anticipated that typical applications would be designed and tested as a part of the project. The responsibility for public applications, i.e. those to be used by the Federal and state governments was assigned to BAH and those likely to be used by the vehicle manufacturers and providers of the commercial services were assigned to the VIIC and their suppliers for development.

The USDOT's Intelligent Transportation Systems (ITS) Joint Program Office provided oversight and program management. Funding for the program was shared between USDOT and the VIIC with the USDOT providing the majority share.

3.4 VII Consortium Formation

The (VIIC was formed in February 2005 by three manufacturers of light-duty vehicles for the specific purpose of actively engaging in the design, testing and evaluation of a deployable VII system for the U.S. The Consortium was also formed to provide a contracting mechanism for the Cooperative Agreement that was later established with the USDOT Federal Highway Administration (FHWA). Initial membership included Daimler-Chrysler, Ford Motor Company and Nissan Technical Center North America, Inc. Subsequently, the membership increased to include BMW of North America, LLC, General Motors Corporation, Honda R&D Americas, Inc, Toyota Motor Engineering and Manufacturing North America, Inc. and Volkswagen of America, Inc. (VW). Since the split of the Daimler-Chrysler organization, both Mercedes-Benz Research and Development North America, Inc. and Chrysler LLC have retained memberships resulting in the VIIC membership totaling nine light-duty vehicle manufacturers at the time of this report publication. The Consortium is a Michigan 501(c)(6) non-profit organization.

3.5 Cooperative Agreement between VIIC and USDOT

A Cooperative Agreement between the USDOT FWHA and the VIIC was executed on December 7, 2005. The objectives of this agreement are:

- Analysis of the requirements to permit the auto industry to provide a coordinated input to the VII Coalition
- Analysis of the requirements and definition of specific design elements of the VII architecture
- Design of specific hardware to facilitate the implementation of the VII system
- Develop software that could be employed either on the vehicle or in the infrastructure
- Fabrication or procurement of equipment to be used in the test and evaluation of the VII program
- Testing of specific elements and / or combinations of elements of the VII architecture
- Integration of elements of the VII architecture to permit evaluation of the design
- Evaluation of the effectiveness of specific designs with respect to the stated objectives of VII
- Analysis of data and results of the VII program.

The period of performance of the Cooperative Agreement is 60 months.

3.6 VIIC Organization

The VIIC organization is detailed in Figure 3-1.

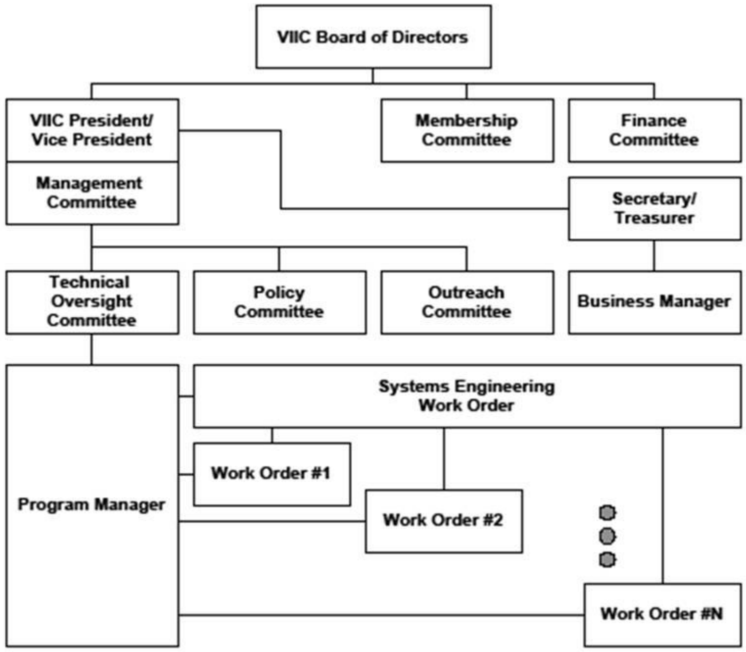


Figure 3-1 VIIC Program Organization

The VIIC Management Committee consisting of members from each of the VIIC participating vehicle manufacturers report to the VIIC Board of Directors, which is responsible for carrying out the charter outlined in the Articles of Incorporation. The Management Committee manages the daily operations of the VIIC through three committees: the Technical Oversight Committee, the Policy Committee and the Outreach Committee. The program is subdivided into a series of twelve (12) Work Orders detailed in Table 1 for executing the technical work, policy and outreach programs.

The Policy and Outreach Committees have jurisdiction over the Policy Work Order (WO) and the Technical Oversight Committee has jurisdiction over the remaining WOs dealing with technical content of the program through the office of the Program Manager. Each WO is managed by a Technical Management Team (TMT) leader who is responsible for the technical direction, delivering the work products and maintaining the schedule for the deliverables.

Work Order #	*Work Order Title*	*Work Order #*	*Work Order Title*
1	Program Management	7	Positioning
2	Systems Engineering	8	Security Framework
3	Radio	9	Testing Lab and Facilities
4	Policy Support	10	Field Operational Test*
5	OBE Subsystem	11	Alternative Analyses*
6	Application Development	12	Private Service Enablers

* Work Orders not activated

Table 1 Cooperative Agreement Work Orders

3.7 VIIC Work Order Description

As mentioned previously, the POC program portion of the Cooperative Agreement was broken down into twelve (12) WOs. The following is a description of each WO as they pertain to the POC. The suppliers in each WO are shown in Table 2.

3.1.1 WO 1: Program Management

POC tasks included program management of the overall project including the delivery of all work products on time and within budget. Tasks also included the oversight of the technical, policy and outreach committees by the Management Committee. Other tasks not included in other WOs were included in this WO.

Deliverables included weekly and quarterly reports detailing progress and expenditure, and quarterly Program Management Reviews.

3.1.2 WO 2: Systems Engineering

Tasks included development of system requirements, allocation of requirements to system components and interface specifications, oversight of interface documentation between WO initiatives, development of test plans and procedures, system and application testing, reports analysis and reporting.

Deliverables included systems engineering and test master plans, VII POC architecture documentation, requirements specifications, requirements allocation documentation, POC test plans and procedures, test results and final test reports.

3.1.3 WO 3: Radio

Tasks included designing a compatible radio based on the IEEE 802.11(p) and IEEE P1609.2, IEEE P1609.3 and IEEE P1609.4 specifications. Also included are the development of specifications and all software and testing of the completed work product. The tasks also included feedback to the standards committees and conducting a scalability study.

Deliverables included radio design specifications, source code for all layers, physical delivery of dual antennas, test plans and results and feedback to the standards committees.

3.1.4 WO 4: Policy Support

POC tasks included guidance on Human Machine Interface (HMI) implementation and analysis of testing implications, antitrust issues, patent analysis and patent guidance.

Deliverables included HMI guidelines, guidance to WO teams concerning federal, state and local law compliance, antitrust guidelines, patent infringement and patent defense analysis, deployment plan and business case recommendations and legal obligations.

3.1.5 WO 5: On-Board Equipment Subsystem

Tasks included the development of various design specifications, selection and procurement of a hardware platform, selection of various operating systems and the development of some of the base services including the HMI, power management and vehicle interface. Also included was the responsibility for integration of all service components resident on the platform but designed in other WOs.

Deliverables included OBE hardware and HMI specifications, production of a number of dual purpose antennas, vehicle interface specifications, protocol documentations, interface and final test procedures.

3.1.6 WO 6: Application Development

Tasks included the development of requirements, design specification and the development and testing of on-board and off-board network components for various applications. The applications developed were In-Vehicle Signage, Probe Data Collection (PDC), Off-Board Navigation, Tolling and Parking Payments and Trip-Path Data Collection.

Deliverables included updated use cases, Software Requirements Specifications (SRS), executable code, unit level and integration test reports.

3.1.7 WO 7: Positioning

Tasks included the development of requirements for a Commercial Off-the-Shelf (COTS) positioning system, procurement and testing of same, and the development of a positioning service and system clock for integration into the OBE.

Deliverables included positioning requirements, Application Programming Interface (APIs), executable software, physical hardware, High Accuracy National Differential GPS (HANDGPS) reference station and final test and qualifications plans and reports.

3.1.8 WO 8: Security Framework

Tasks included the development of a security system generally in accordance with IEEE 1609.2. This included the development of requirements and design specifications for the framework and the development and integration testing of the system components for both the OBE and. The system components included the Certificate Authority (CA), Certificate Manager (CM), Security Cryptographic libraries and a hardware accelerator to support the libraries. Also included was a study of security system vulnerability.

Deliverables included security concept of operations, scalability and threat analysis white papers, CM process specification, POC software architecture and SRS, executable code, software libraries, hardware accelerator boards and probe data encoder.

3.1.9 WO 9: Testing Lab and Facilities

Tasks included the completion of all test plans and procedures, the testing of Communication, Positioning, Vehicle Interface and Security services, integration testing and final testing of applications as part of system end-to-end testing. Also included in the WO were tasks to analyze all results and develop associated reports.

Deliverables included critique of all test plans prepared by others, subsystem component and test equipment supply, test plans and procedures for all services and applications integration test plans, test results for all services testing and final test reports.

3.1.10 WO 10: Field Operational Testing

This WO has not been developed or funded.

3.1.11 WO 11: Alternative Analysis

This WO has not been developed or funded.

3.1.12 WO 12: Private Service Enablers

Tasks included the development of requirements for methods to connect private services to the network in order to conduct point-to-point transactions across multiple RSEs. Included in the WO were the development of OBE and network components and associated protocols to facilitate point-to-point transactions.

Deliverables included requirements specifications, VII POC architecture design, component analysis and selection, software specifications, executable code and acceptance test plans and results.

3.8 VIIC Supplier Selection

The design of a complex system required the expertise of companies with a wide range of diverse skills ranging from automotive electronics to networking systems. It was also recognized that the inclusion of a significant number of suppliers in the program would involve related industries and help to accelerate industry involvement. Invitations to submit proposals were sent to approximately 100 suppliers known to have an interest and the capabilities to develop the VII system. Proposals were reviewed and selections of the final supplier candidates were made by the program team including the VIIC membership. Table 2 details the supplier involvement for each WO.

Supplier	WO Number									
	1	2	3	4	5	6	7	8	9	12
ABSS Inc.	X									
ARINC Inc.							X			
Battelle Institute		X							X	
BMW	X		X	X	X					
Chrysler LLC.	X		X	X	X	X			X	
Cogenia Partners LLC.	X	X						X	X	
Delphi Automotive Systems Inc					X	X				
Denso International America,			X		X					
Dykema Gossett				X						
Ford Motor Company	X			X		X			X	
Honda R&D Americas Inc.	X			X					X	
Intel Americas Inc.										X
Mark IV IVHS Inc.						X				
Mercedes Benz	X		X	X	X					

Moser Racing LLC.	X									
MTS LLC.						X				
Navteq North America LLC.						X				
Nissan Technical Center NA	X			X			X			
Ntru Cryptosystems Inc.								X		
Parvus Corporation					X					
Prosyst Software Gmbh.					X					
Raytheon Company						X			X	
Roush Industries									X	
Sirit Technology Inc.			X							
Technocom (now Kapsch TrafficCom)			X					X		X
Telcordia Technologies								X	X	
Toyota Motor Engineering and Manufacturing NA Inc.	X			X					X	
Transcore LP.			X							
Volkswagen	X			X	X					
WFET Group		X							X	
Wind River Systems Inc.					X					

*WOs 10 and 11 not initiated

Table 2 VIIC Supplier Involvements in WOs

3.9 Collaboration Agreement between VIIC and Suppliers

The Collaboration Agreement was developed to protect the intellectual property right of the WO Suppliers. The Collaboration Agreement was used in WOs where intellectual property was likely to be used or developed. Each WO was supported by a number of suppliers as detailed in Table 2. As a result of the Collaboration Agreement, these teams of suppliers were able to work collaboratively in a pre-competitive environment.

3.10 Infrastructure Program

BAH acted as the system integrator for the infrastructure and public applications, while the VIIC led the development and testing of the OBE, and private applications including test applications to determine the systems capability to support safety applications. The BAH team consisted of Iteris, Sirit, Technocom and Telcordia. Local support in Michigan was provided by the Michigan Department of Transportation (MDOT) and Road Commission for Oakland County (RCOC).

	Prgram Mgmt	System Eng	SDN	ENOC &CA	RSE	DTE	SIT	Public Apps	POC Testing	O&M	Stds
Booz Allen Hamilton	X	X	X	X	X	X	X	X	X	X	X
Iteris		X						X			X
MDOT/RCOC						X			X	X	
Raytheon		X			X	X	X				X
Sirit					X		X				
Technocom/Kapsch					X		X				
Telcordia		X	X	X			X				

Table 3 Roles and Responsibilities of Booz Allen Team

3.11 Combined Program Management Process

Formal program management processes were applied as appropriate for the size and complexity of the program. The need for this was accentuated by the number of WOs, (the relatively large number of suppliers spread across two continents), and the assignment of responsibilities between VIIC and BAH as described in Section 3.3. To achieve this goal, the program was broken down into the following tasks:

1. Collect stakeholder requirements.
2. Develop a concept of operations for the system based on stakeholder requirements.
3. Develop requirements for the system concept and its components.
4. Develop or procure the components according to the requirements.
5. Assemble and deploy a small scale version of the system.
6. Perform integration testing.
7. Perform system testing against performance specifications.
8. Analyze results and determine if the viability criteria for the system had been met.
9. Report on the findings of the program.

The formal processes employed to manage the program included:

- Weekly WO program progress meetings with the TMT leaders chaired by the Program Manager.
- Weekly WO supplier progress and technical meetings chaired by TMT leaders.
- Weekly coordination meetings between VIIC and BAH.
- Weekly reporting to the USDOT.
- Quarterly Program Management Reviews with the USDOT and supply community.
- Engineering Review Board Meetings (VIIC only).
- Configuration Control Board Meetings.
- System Integration Team meetings to review and discuss component interfaces and operation.
- These meetings were, on occasion, held on a daily basis to resolve difficult and urgent technical issues.

Tools used for program management included Microsoft Project for project scheduling and task completion assessment and QuickBooks for project accounting.

4 VII POC Test Results and Findings Summary

The POC system testing generally indicates that the system performed all of the core functions (See Section 4.2) identified for the VII system. The program involved implementation and test of numerous features defined in the original VII architecture, and resulted in the development of a significant knowledge base related to feasibility and future implementation of these subsystems and features. The POC tests indicate that the system concept is technically feasible and performs well under most conditions. The tests clearly identified areas where performance can be improved, and areas where the concepts can be refined, but overall the POC development and system test results represent a significant step forward in achieving the original vision that VII may offer.

The following sections summarize the key findings gained from the variety of laboratory, track and on-road tests. These are laid out in terms of the specific system services to which they most closely relate. Commentary has also been provided to link these findings to the viability criteria and the core operational objectives of the system.

4.1 VII POC Test Objectives

The objectives of the POC tests were to assess the overall ability of the system to perform the core functions (described in Volume 2a), and to measure the performance of the system along various dimensions. The tests were divided into quantitative assessments of specific functional services in the system (DSRC Communications, Positioning, Security, Vehicle Interface, etc) and assessments of representative applications, specifically, Geographic Advisory messaging, Probe Data Collection (PDC), Vehicle to Vehicle (V2V) messaging, transactions involving local service provider communication with an RSE (i.e. not through the VII network) and network transactions that involve OBE encounters with multiple RSEs.

The tests were performed using a combination of test equipment (for direct measurements) and test applications. The test applications were not designed to behave as production implementations, but were representative of such applications, and were intended to exercise specific behaviors and features of the overall system. While it was not the intent to perform extensive demonstrations of the system using these applications, they were also used for this purpose.

4.2 VII POC Test Approach Overview

The system integration and test program was performed in three multi-phase segments. As shown in Figure 4-1, the OBE functionality and vehicle integration was initially tested in a garage/lab environment. This allowed rapid troubleshooting and early assessment of functionality. The system services were then tested in both laboratory and test track environments. This provided for detailed quantitative measurement of the capability and performance of these services. Some system services, for example DSRC Communications, were also assessed in open road environments in California (hilly, curved roads and urban canyons).

Following the assessment of the basic system services, a detailed assessment of the POC applications were conducted using the test track environment. This allowed for early troubleshooting and refinement of the applications, which were then fully assessed in the open road, DTE. The DTE tests included a combination of quantitative measurements in both track and DTE environments and qualitative road tests to assess basic functionality and behavior.

This staged sequence of integration and test allowed a systematic increase in complexity as the various features of the system were incorporated.

All of the track and DTE road testing was completed without the security features activated. This was partly due to schedule constraints (the Security WO started rather late in the program), and partly to establish a performance baseline without security to allow later assessment of the impact of the security functions. Once the overall system tests were complete, a subset was re-run with the security functions activated.

The Garage, Track and DTE segments were carried out in several phases, each of which built on the prior phases of all three segments. These are shown in Fig 4-1.

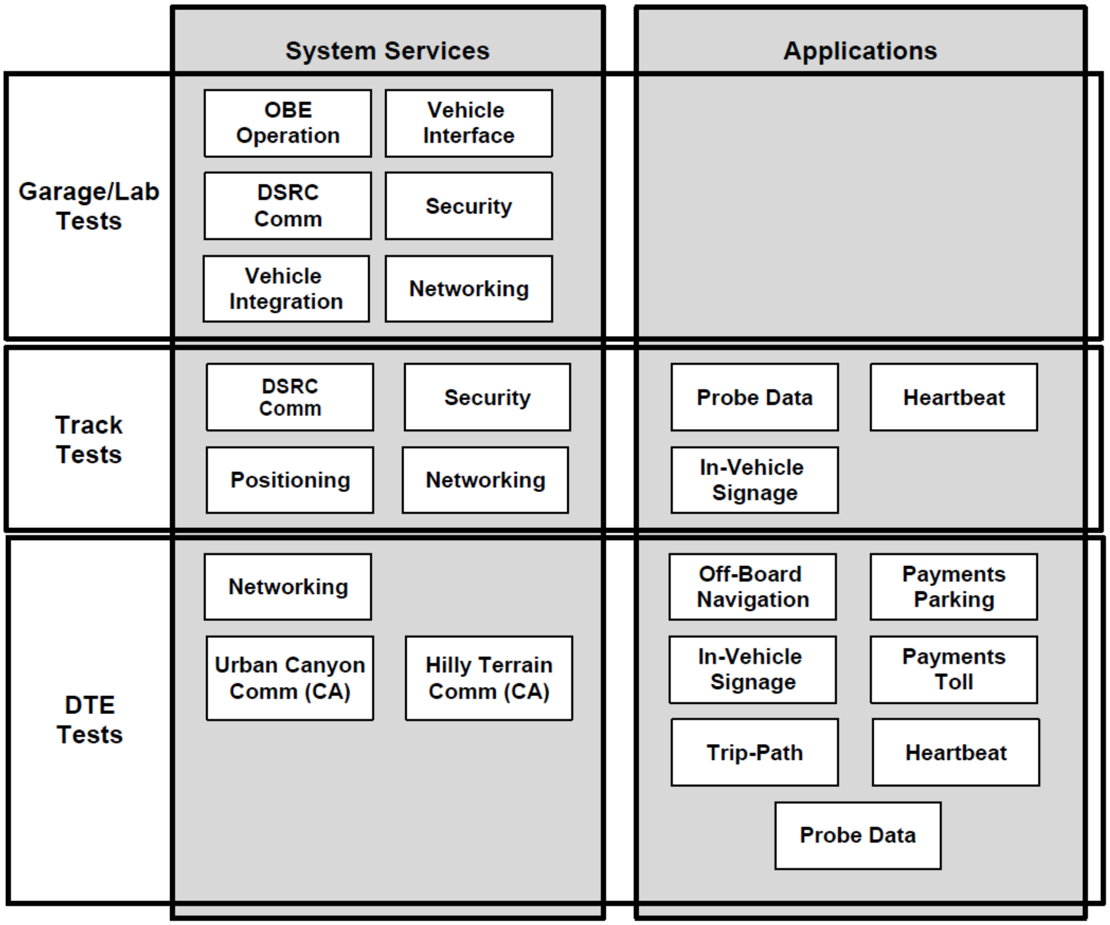


Figure 4-1 POC Test Structure

4.3 On-Board Equipment Subsystem Results and Findings

The OBE is based on shared services architecture. These services were individually tested, the results of which are detailed below.

4.3.1 DSRC Communications Test Results and Findings

The objective of the DSRC Communications test was to verify that the OBE subsystem was integrated and able to communicate with the VII RSE and verify that the performance of the 5.9 GHz DSRC link is able to support the needs of the intended applications.

4.3.1.1 DSRC Communications Test Overview

The DSRC link was tested for Vehicle to Infrastructure (V2I) and V2V communications under static and dynamic situations, and under various interference and aspect angle conditions.

Four configurations of the VIIC fleet vehicles (Ford Edge, Jeep Cherokee, Nissan Altima and Toyota Camry) were tested in an open-area environment to establish a baseline level of performance. Two additional vehicle configurations (VW Passat and Rabbit) were also tested in urban canyon and hilly terrain environments. The test scenarios are described as follows:

DSRC-1: DSRC Link Static Performance, V2I

The goal of this test is to measure packet throughput, packet loss, burst error length, and signal strength that comprehensively indicate the performance of various link configurations for V2I communication. The link configurations to be tested include Control Channel (CCH) broadcasts of long and short Wave Short Message (WSMs) and Service Channel (SCH) unicasts of long and short Universal Datagram Protocol (UDP) messages.

This test is designed to verify vehicle and infrastructure communication while operating at a series of static distances. The position of each test point is determined based on a percentage of the observed communication range corresponding to a 10% Packet Error Rate (PER). This test was repeated for a total of 15 test points ranging from 10% to 150% of this range. The test setup is illustrated in Figure 4-2.

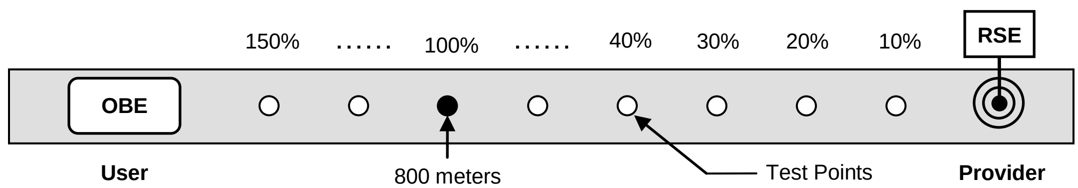


Figure 4-2 DSRC-1 V2I Communications Test Setup

DSRC-2: DSRC Link Static Performance, V2V

The goal of this test is to measure packet throughput, packet loss, burst error length and signal strength that comprehensively indicate the performance of various link configurations for V2V communication. The link configurations to be tested include CCH broadcasts of long and short WSM. This test is designed to verify V2V communication while operating at a series of static distances. The position of each test point is predetermined based on a percentage of the observed communication range corresponding to a 10% PER. This test was repeated for a total of 15 test points ranging from 10% to 150% of this range. This test setup is illustrated in Figure 4-3.

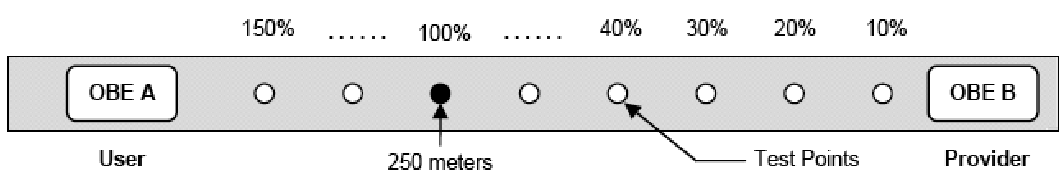


Figure 4-3 DSRC-2 V2V Communications Test Setup

DSRC-3: DSRC Link Aspect Angle

This test is designed to verify vehicle-to-link orientation of a typical vehicle at different azimuth and elevation angles. The tests were performed by Southwest Research Institute (SwRI).

The test was performed by placing a vehicle fitted with a DSRC antenna on a rotating turntable. A DSRC source was then placed on a variable height mast, and the signal strength was measured in the vehicle at a variety of vehicle azimuth positions and with the DSRC source placed at various heights to control the elevation angle. The test setup is shown in Figure 4-4.

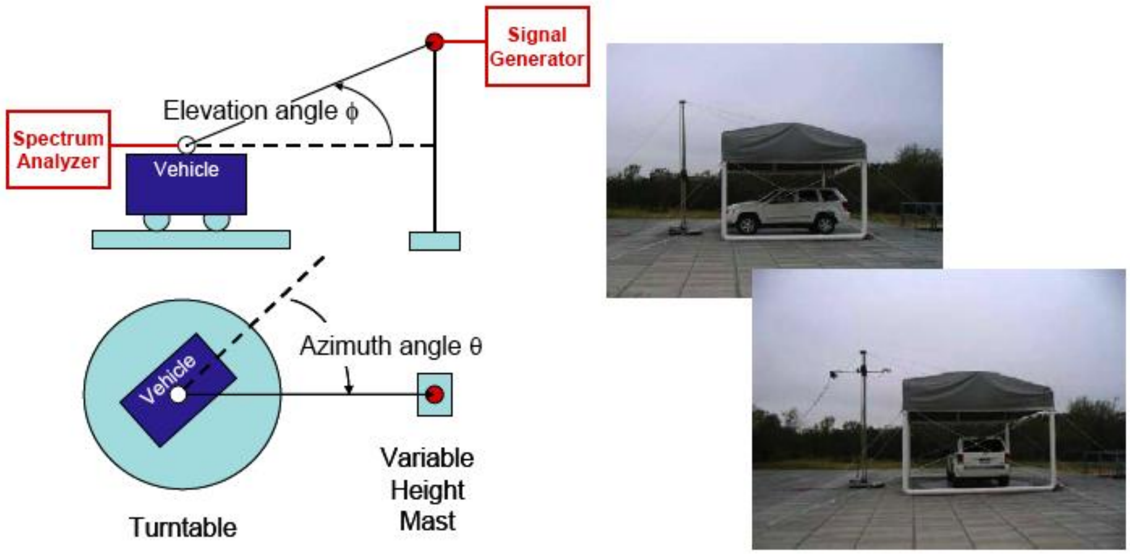


Figure 4-4 Aspect Angle Communications Test Setup

DSRC-4: DSRC Dynamic Performance

The goal of this test was to measure packet throughput, packet loss, burst error length and signal strength that comprehensively indicate the performance of various link configurations as a function of vehicle speed.

The RSE was configured to transmit and receive WSM and UDP messages to and from the OBE as the OBE test vehicle moves into the effective range of the RSE, turns around, and drives back out of the RSE range. The range at which packet PER achieves 10% was recorded. The test was repeated at a total of three vehicle speeds of 30 mph, 50 mph and 70 mph and with the RSE transmission power set to 15 dBm and 11 dBm. The test setup is illustrated in Figure 4-5.

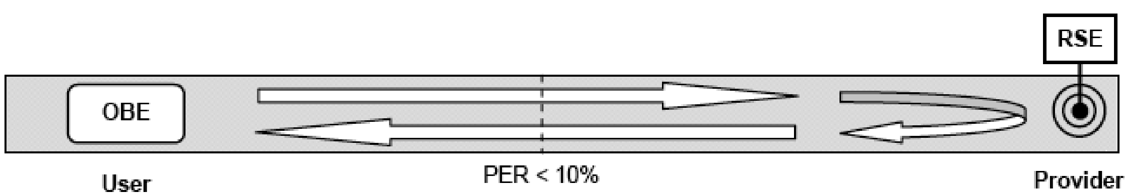


Figure 4-5 Dynamic Communications Baseline Test Setup

DSRC-5a: DSRC Link Mutual Interference, V2I

The goal of this test is to measure packet throughput, packet loss, burst error length, and signal strength that comprehensively indicate the performance of various link configurations for V2I communication while operating with mutual interference.

This test is designed to verify V2I communication while operating at a series of static distances in an environment of mutual interference. The position of each test point is determined based on a percentage of the observed communication range corresponding to a 10% PER. This test was repeated for a total of 15 test points ranging from 10% to 150% of this range and the entire test was repeated for a total of four Heartbeat message interference rates of 10 Hz, 16 Hz, 25 Hz, and 50 Hz. The test setup is illustrated in Figure 4-6. Six interfering vehicles were used for this test.

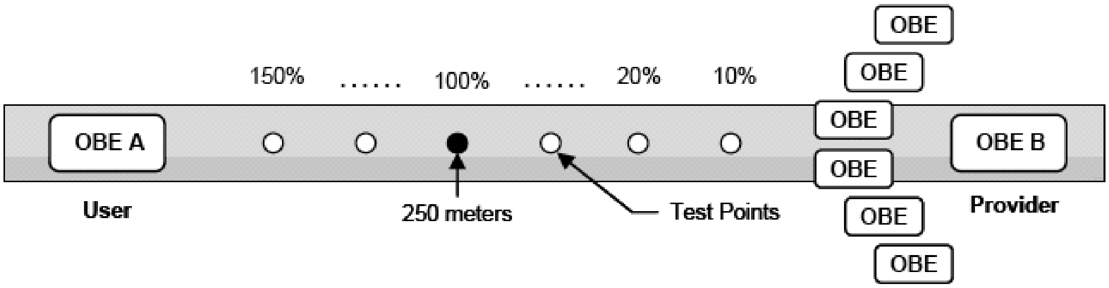


Figure 4-6 DSRC Mutual Interference Test Setup

DSRC-5b: DSRC Link Mutual Interference, V2V
The goal of this test is to measure packet throughput, packet loss, burst error length, and signal strength that comprehensively indicate the performance of various link configurations for V2V communication while operating with mutual interference. The test results shall be compared to those obtained from DSRC-2 to determine the degradation in the radio link performance and the interference rate. The link configurations to be tested include CCH broadcasts of long and short WSM.

This test is designed to verify V2V communication while operating at a series of static distances in an environment of mutual interference. The position of each test point is determined based on a percentage of the observed communication range corresponding to a 10% PER. This test was repeated for a total of 15 test points ranging from 10% to 150% of this range and the entire test was repeated for a total of four Heartbeat message rates of 10 Hz, 16 Hz, 25 Hz, and 50 Hz. The test setup is illustrated in Figure 4-7.

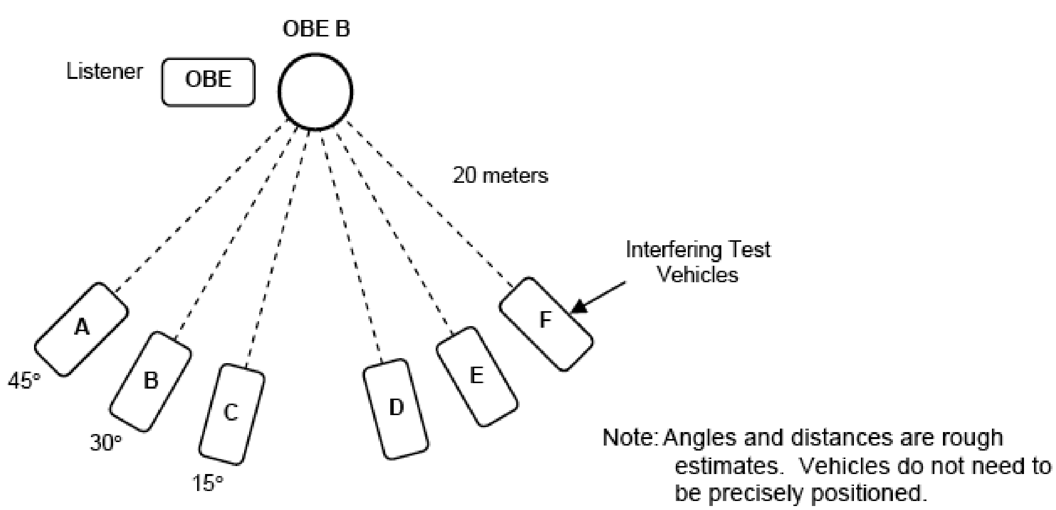


Figure 4-7 DSRC-5b Test Setup

Urban Canyon Testing

DSRC-1 through DSRC-4 testing was also performed in an urban canyon environment and evaluated and compared to the results collected from the open area testing to assess the impact of the urban setting on the performance of the DSRC communication link. The test sites are shown in Figures 4-8 to 4-10 below.

Figure 4-8 Low Urban Canyon

Figure 4-9 Medium Urban Canyon

Figure 4-10 Tall Urban Canyon Test Environment

Hilly Terrain Testing

The hilly terrain testing was performed on Highway 1, south of San Francisco, at three test locations representing various terrains, including occulted and crested hills and curves. The RSE was positioned at the side of the road at each location as shown in Figures 4-12 and 4-13.

Figure 4-11 Hilly Location #1

Figure 4-12 Hilly Location #2

Figure 4-13 Hilly Location #3

4.3.1.2 Communications Service Test Observations/Findings

This section summarizes the key observations and findings from the DSRC Communications tests. For further detail and data, see Volume 4a.

DSRC Range

The V2I and I2V range was found to significantly exceed original estimates. In open field conditions with no roadside furniture, the V2I range was found to exceed 800 m and the I2V range exceeded 1200 m using transmit powers of 11 dBm and 15 dBm, respectively and the low-profile vehicle dual antenna.

DSRC Reception Nulls

The DSRC testing revealed the presence of a null point in the RSE-OBE (I2V) radio signal at a range of about 300 m. This null point is the result of a well-documented issue where a radio signal takes multiple paths from the source to the destination and at certain distances the signals destructively interfere. This null point can cause the radio signal strength to drop below the receive threshold of the OBE radio / antenna combination, resulting in lost data. A similar null-point was also observed in the OBE-OBE (V2V) radio signal located at about the 100 m range. In the open-area environment the radio null points were relatively clearly defined, however observations made in a reflective environment (e.g. urban canyons) revealed that the null region was less defined which had a mitigating effect on the impact to the DSRC communication link.

The height of the vehicle profile had a significant impact on the effective range of the DSRC communication link. It was found that the high-profile vehicles (Cherokee, Edge) had a reliable I2V communication range of about 800 m while the low-profile vehicles (Altima, Camry) had a range of about 600 m. This behavior can be seen in Figure 4-14.

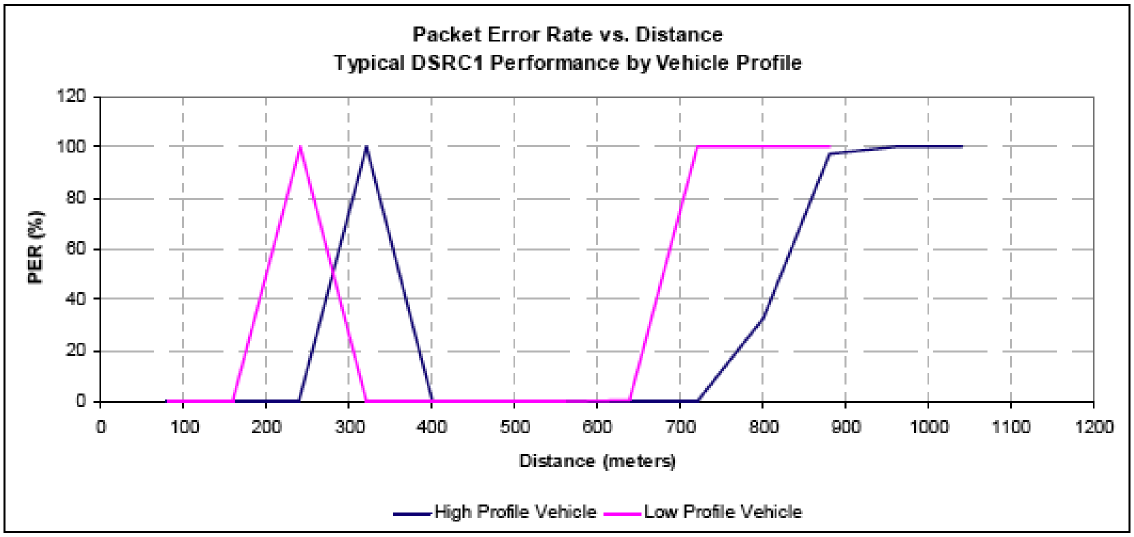


Figure 4-14 V2I DSRC Range in Open Field Environment

The V2V communication link between high-profile vehicles was effective to a range of about 250 m, however, when a low-profile vehicle was tested its range was only about 50 m. This caused the low-profile vehicles to fail the acceptance criteria for V2V communication, which requires a reliable range of 100 m. This behavior can be seen in Figure 4-15.

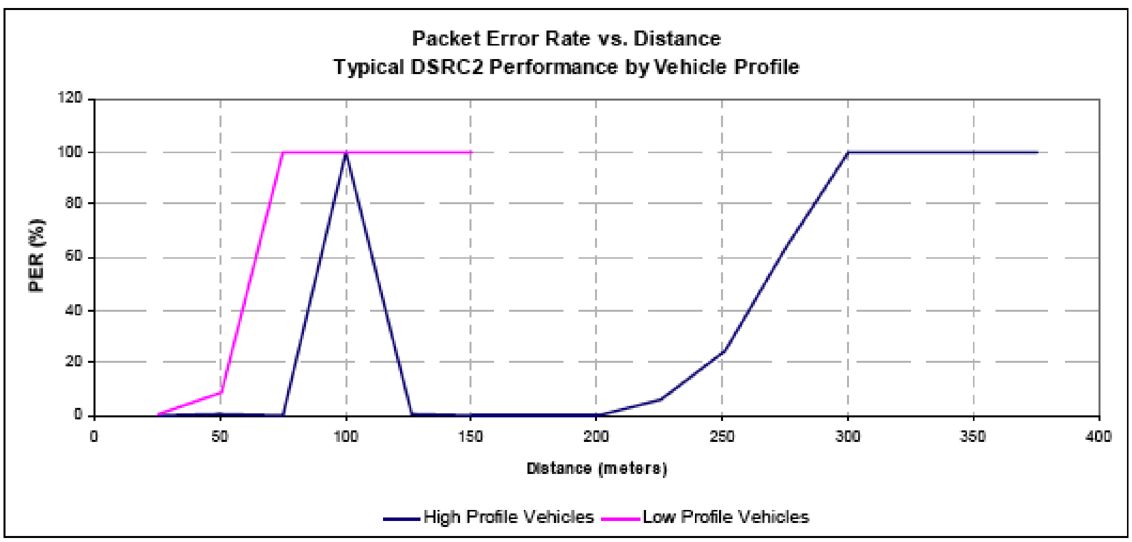


Figure 4-15 V2V DSRC Range in Open Field Environment

In general, the occurrence of multipath fading is not unexpected. Most radio systems exhibit this behavior, especially in mobile applications. The simplest solution is to use two antennas placed slightly apart from one another. This has the effect of creating additional paths from reflecting surfaces, and the separation between the antennas assures that one of the paths will not cancel (See Section discussing Urban Canyon Impacts).

DSRC Link Imbalance and Unexpected Service Joins

An imbalance was observed between the transmission range for the WAVE Service Announcement (WSA) messages and the reliable range for two-way data exchanges. In this situation, a WSA is received by the OBE at an extreme range where reliable communication is not normally expected. With the right combination of the registered OBE application and advertised service, and since the reception of a single WSA is all that is required for the OBE to "join" the RSE service, the OBE joins and begins transmitting data. This can occur at long ranges because there is a finite chance that, for example, even at 99% PER, one WSA (out of one hundred broadcasts) will get through. However, the RSE has higher transmit power than the OBE, so at these long ranges, it is typically not possible for the OBE to successfully send packets back to the RSE. This is illustrated below in Figure 4-16.

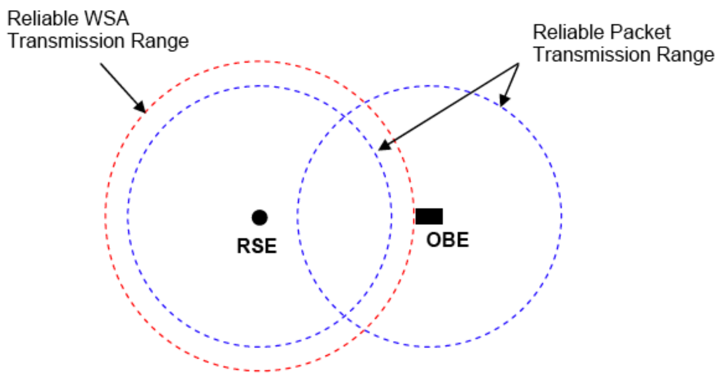


Figure 4-16 RSE/OBE Link Imbalance

The system worked well for those applications utilizing only broadcast messages, such as Signage. Without this problem being rectified, it is less suitable for applications requiring two-way communications. This issue also caused substantial problems in early application testing. The mechanism is well understood, and the radio protocols need to be revised, so that the radio does not join a service unless the quality of service is acceptable.

DSRC Message Congestion

The effect of mutually interfering transmissions on DSRC CCH communications was evaluated for the purpose of assessing the impact of crowding the CCH with a large number of WSM packets. An increasing number of packet errors were observed in the WSM traffic as the interference level increased. The acceptance criteria for this test required a PER of less than 20% to successfully pass. The PER percentage for this test reached the 20% level, with an interference rate of about 150 WSM messages per second. As expected, long messages (1200 bytes) were affected more significantly than short messages (300 bytes), because the longer messages consume more overall channel time per message.

The results of this test are shown in Figure 4-17.

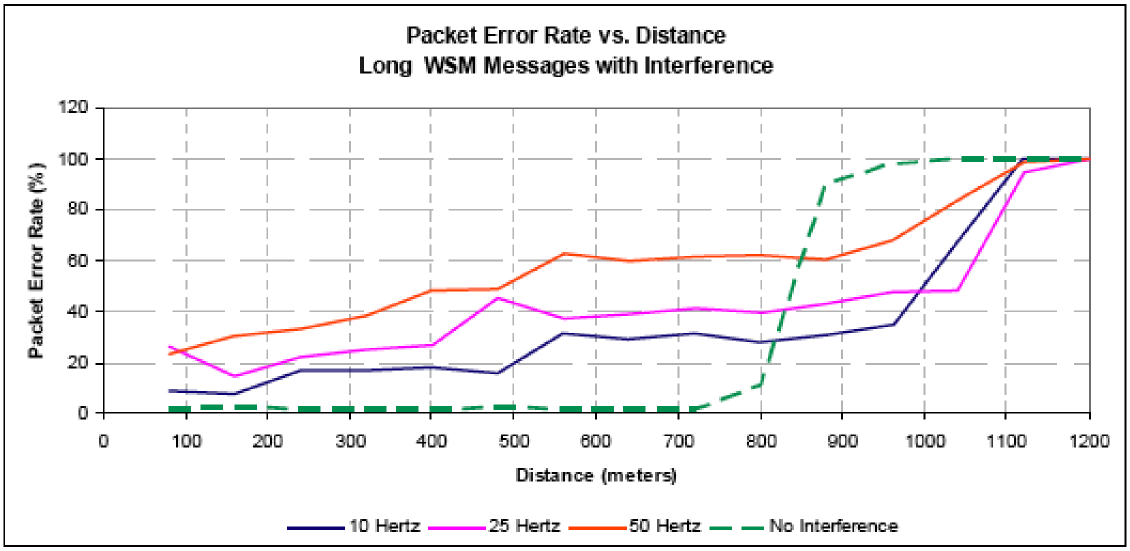


Figure 4-17 Effect of Control Channel Congestion

The same test was run using UDP message traffic on the SCH. As expected congestion on the CCH did not impact communications on the SCH. It was, however, observed that UDP messages (which are limited to using only the SCH) were generally received more reliably under all conditions than WSMs . This appears to be a direct result of the built-in low-level message acknowledgement and retry processes used for unicast UDP packets in the IEEE 802.11/802.2 standards. Multicast UDP packets were not tested, but it is expected that they would exhibit similar behavior to the WSM tests.

The same test was run using UDP message traffic on the service channel. As expected congestion on the Control channel did not impact communications on the Service channel. It was, however, observed that UDP messages (which are limited to using only the Service Channel) were generally received more reliably under all conditions than WSM messages. This appears to be a direct result of the built-in low-level message acknowledgement and retry processes used for unicast UDP packets in the 802.11/802.2 standards. Multicast UDP packets were not tested, but, since they are also not acknowledged and subject to retries, it is expected that they would exhibit behavior similar to the WSM tests.

It is also important to point out that the WSM tests described in this section may indicate an abnormally high packet loss rate because of the control channel synchronization. This issue is described in the next section.

Medium Access Control Issues

The channel switching concept and synchronization as defined in IEEE P1609.3/P1609.4 was shown to provide the intended functionality, namely, that all CCH messages are received by all listeners and during the SCH interval, the opportunity to transmit messages is provided. However, during initial track testing of the Heartbeat message the message loss rate was observed to follow the Heartbeat rate. As Heartbeat rate increased, the percentage of messages lost also increased. Further analysis indicates this is due to a basic problem in the IEEE 802.11p DSRC protocol. The IEEE 802.11 protocol uses a system known as Carrier Sense Multiple Access (CSMA) to avoid interference caused by transmitters sending messages at the same time. The system requires each transmitter to listen to the channel prior to transmitting a message. If the channel is clear (no other radio activity), then the message may be sent. If the channel is not clear (radio activity detected), then the transmitter randomly selects a “back-off interval.” When this back-off interval expires, it once again checks the channel. When many radios are trying to send messages, the messages are distributed randomly over time. As long as there is enough time, then all messages will eventually be sent. This concept works well in environments where the users are all transmitting messages asynchronously (for example, WiFi users sharing the same channel do not all send or receive data at the same instant).

However, this assumption of asynchronism is not valid in IEEE 802.11p, since IEEE P1609.3/P1609.4 defines a CCH interval and a SCH interval. By requiring that all safety messages be sent on the CCH during a specific time interval, and that all users monitor that channel during that interval, the system assures that safety messages are sent when others are listening. Without this requirement, a radio could easily be tuned to one of the SCHs when a safety message was sent, and the message would not be received. Unfortunately the effect of the CCH interval is to synchronize the users.

Under normal CSMA operation, the users begin their transmission by listening, and then, either sending a message on a clear channel, or choosing a random time and then listening again. In IEEE 802.11p, the users choose a back-off interval at the beginning of the CCH interval, and then listen. This is intended to avoid all users bunching up at the start of the CCH interval. However, there are only a finite number of back-off intervals to choose from, so as the number of users rises, the chance that they will pick the same initial back-off interval rises. If they happen to pick the same interval, then when they listen, the channel will be clear and they will both transmit at the same time. The resulting interference causes both messages to be lost. As the rate increases, this process gets carried out over and over because every time the channel is busy, the sender chooses another back-off time, and this is another opportunity for a different user's transmission to collide. Note, that this happens even when the users chose different time spots, because they may have chosen their new back-off times at points that differed by a complimentary amount, to the difference of their earlier back-off times. This effect was modeled and the results indicate a high likelihood that this is the cause of the lost messages.

The solution to the problem is not difficult. The standard IEEE 802.11 CSMA specification uses only seven back-off intervals. As a result there is a very high likelihood that two users will choose the same time when they start at the same time (the start of the CCH Interval). If the size of the "contention window" is increased to support, for example 256 back-off intervals, then the probability that users will choose the same interval is much smaller, and the opportunity for collisions will decline substantially. This change needs to be brought to the DSRC standards committees.

Channel Synchronization Latency

It was observed during security testing that message latency was somewhat random, and at times exhibited a bi-modal distribution. These distributions appear to be separated by approximately 50 milliseconds. Analysis and subsequent controlled tests indicates that this is an unexpected result of asynchronism between the sending application and the DSRC radio channel switching. The DSRC Radio set s the channel interval timing based on the 1 Pulse per Second (PPS) signal from the GPS receiver. This is done to assure that different VII terminals (OBEs and RSEs) are all listening to the Control CCH during the CCH interval. However, the applications are not synchronized, and for some applications there may be no simple mechanism to implement any form of synchronization. As a result, applications that, for example, send messages on the CCH may submit their messages at any time. This means that at times the message will pass through the system and into the RF medium with only minimal processing delay, while at other times the message may sit in a queue for a period ranging between zero and one channel interval (in the POC, about 50 msec).

This effect is especially prevalent at higher messaging rates, where about half of the messages are sent with minimum delay, and the other half are distributed over the channel interval, depending on their sending rate.

While the latency times are relatively small (50-100 msec), the result is that these messages may become clumped together at the start of their associated channel interval (CCH or SCH, depending on the application). This aggravates the channel synchronization based congestion issue described above, and also opens the door to out of order messages, since message separated by only a few milliseconds may pass each other in the non-synchronized threads of the receiving terminal software system.

It is unclear how to resolve this issue given the current channel switching approach specified by the DSRC standards.

Urban Canyon Impacts

Various urban canyon heights were tested to assess the impact of the urban setting on the performance of the DSRC communication link. The chosen test sites presented challenges to this assessment, due to the impact on the test results from factors other than the urban setting such as grade elevation changes, traffic conditions, and non-baseline test vehicles. These other factors serve to cloud any conclusions based on a comparison with the open-area testing. However, the testing for the short, medium and tall urban canyons did indicate an apparent positive trend of increasing the effective I2V DSRC communication range while mitigating the effect of the RSE-OBE radio null as the height of the urban canyon increased. This is appears to be a result of the larger number of scattered signal paths present in the urban canyon environment (many multipath sources). This results in the nulls effectively being “filled in” by radio energy scattered from other parts of the local environment. Effectively, the “two ray” multipath model does not hold in these environments. This phenomenon improves the short range communication capability while still providing adequate range for the urban environment. The results of V2I tests in short and tall urban canyon environments are shown in Figure 4-18 and 4-19.

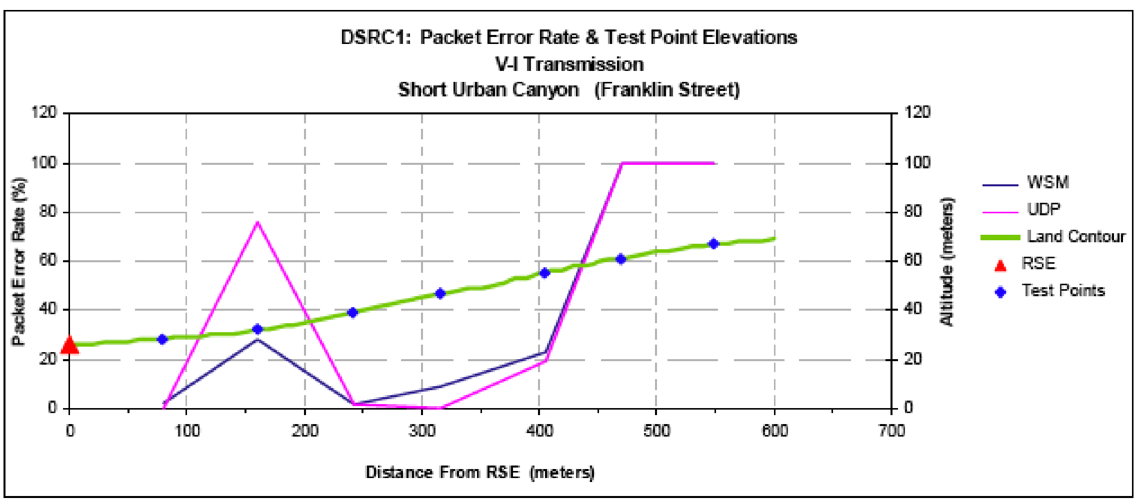


Figure 4-18 DSRC V2I Range in Low Urban Canyon Environment

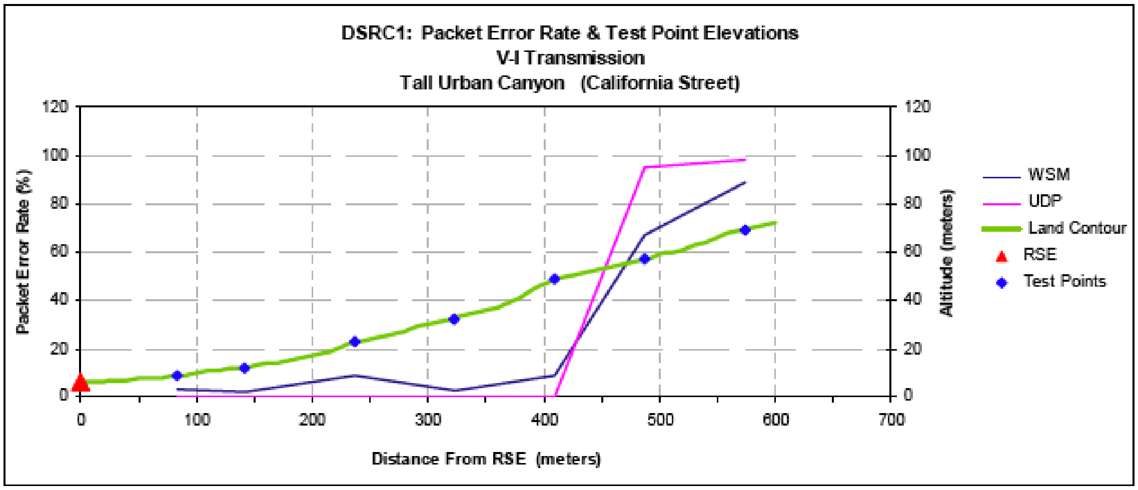


Figure 4-19 DSRC V2I Range in Tall Urban Canyon Environment

Figures 4-20 and 4-21 show the reception quality (PER) vs. range for V2V communication in the short and tall urban canyon regimes respectively. As can be seen by comparing Figure 4-21 to Figure 4-15, the nulls occur at approximately 100 m. Both urban canyon scenarios appear to create greater opportunity for multipath cancellation at longer ranges, and the result is that communications outside the first 100 m null are substantially worse in the urban canyon environment.

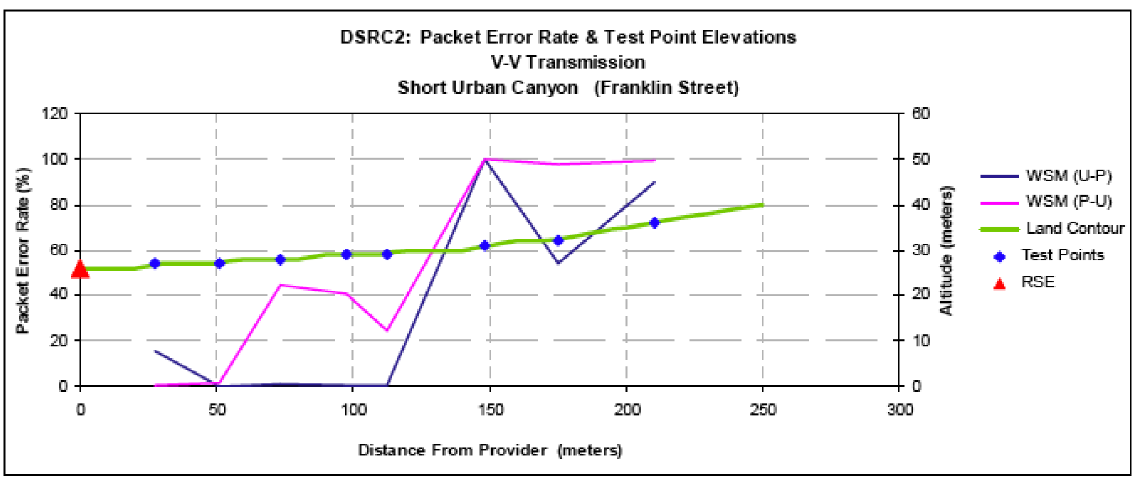


Figure 4-20 DSRC V2V Range in Low Urban Canyon Environment

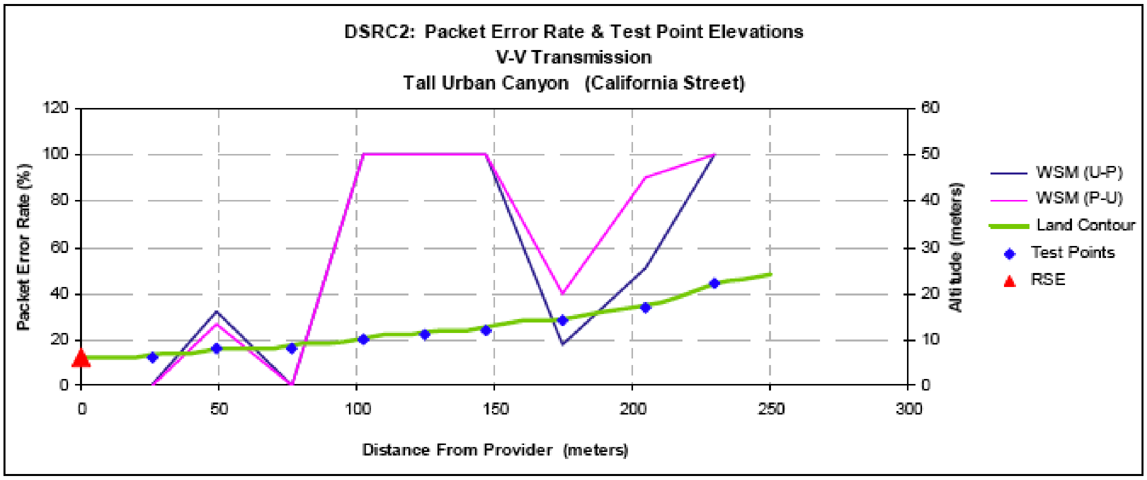


Figure 4-21 DSRC V2V Range in Tall Urban Canyon Environment

Hilly Terrain Impacts

DSRC testing was also conducted in a hilly terrain environment. This testing confirmed that communication between the RSE and vehicle is dominated by line of sight propagation. Observations made in the hilly terrain environment indicate that the location of the nearest obstruction will likely establish the effective range of the DSRC link. Also, the RSE radio (multipath) null was not readily observed in the hilly terrain testing. This is likely due to a combination of two factors. First, the reflective environment mitigates the severity of the null region; and second, physical obstructions such as crested roadways or occulted curves often limit the line of sight with the RSE until the vehicle is already within the typical 300 m range of the null region.

OBE Radio Sensitivity Envelope

The dual antenna concept was successfully implemented for the POC testing. The concept demonstrated that a low profile package that can accommodate both DSRC and GPS antennas is practical, although refinement of the current design is required.

The DSRC received signal strength performance of the Mark IV, combined DSRC and GPS antenna, varied considerably as a function of the link aspect angle. At the time the test was planned, it was expected that the variation would be less than 5 dB. The test results found that, in general, there was about a 10 dB variation between the maximum and the minimum values, but there were also specific aspect angles where the received signal strength dropped by more than 15 dB. The implication of this finding is that vehicles that are in motion with respect to the RSE may encounter link aspect angles with significantly less signal strength. This is particularly true at 30°, 105°, 190° and 330° azimuth angles. The data for this test are shown in Figure 4-22.

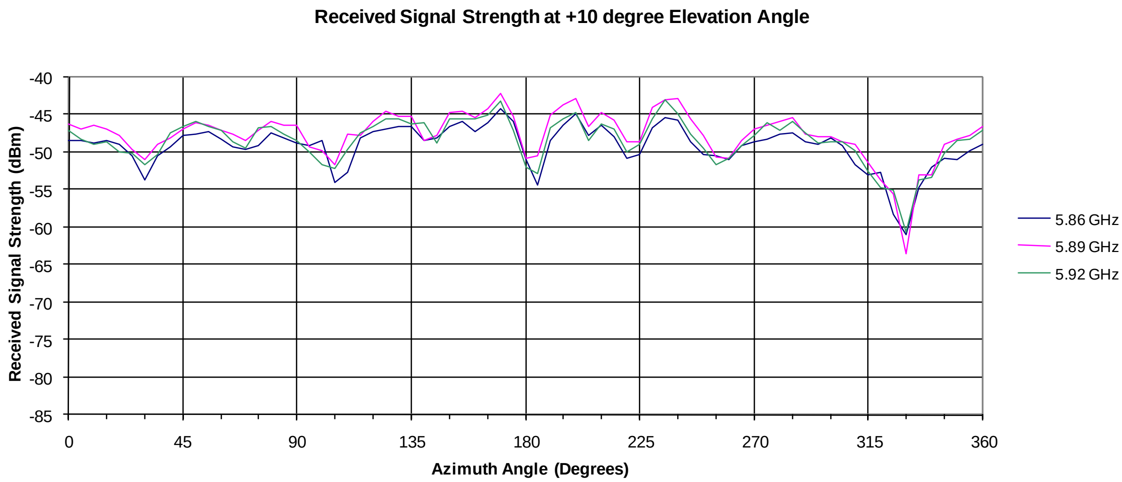


Figure 4-22 Receive Signal Strength vs. Azimuth Angle

Similar effects were also observed during V2V Heartbeat Application testing. In those tests it was found that the antenna position on the roof of the vehicle had a significant impact on the reliability of V2V communications. It is clear that in order to assure reliable communications between a wide variety of different vehicles, it will be necessary to define a minimum required radio performance envelope for mobile elements (e.g. vehicles). This requirement will need to be defined in terms of minimum radiated power vs. azimuth within minimum and maximum elevation angles (for transmitters) and in terms of minimum sensitivity in azimuth and elevation.

4.3.2 Positioning System Tests

Testing of the off board position systems including a test overview, description of the test facilities and equipment and findings are discussed in the following sections.

4.3.2.1 Positioning System Test Overview

The positioning system tests were designed to assess the performance of several aspects of the positioning system: latency of augmentation/correction data delivered by the VII network and two different GPS technologies. The tests were divided into static tests performed in a laboratory and dynamic tests performed on a test track and on the open road. These are summarized below.

Position-1 Augmentation Latency

The goal of this test was to determine the time for position correction messages to travel from the server to the OBE via the RSE and from the OBE to the external positioning unit. The augmentation latency tests were conducted in the VIIC garage using a stationary vehicle. The test setup used is shown in Figure 4-23.

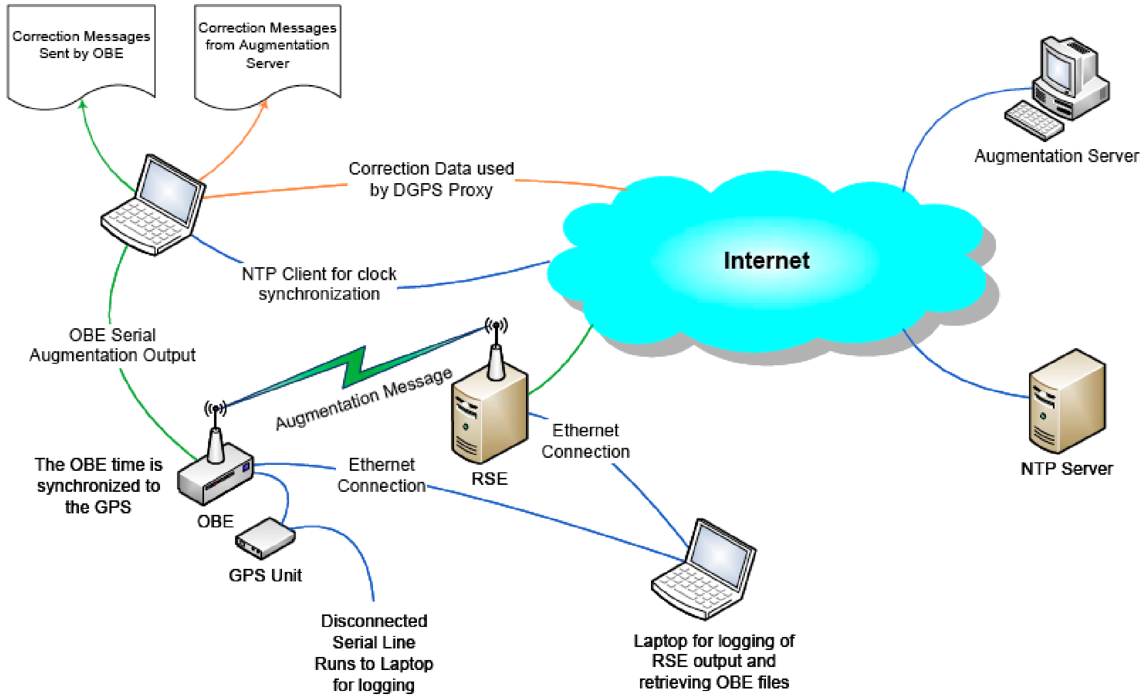


Figure 4-23 Augmentation Latency Test Setup

Three custom applications were written to capture the test data. One application, the Differential Global Positioning System (DGPS) Proxy, was written to collect augmentation data directly from the augmentation server via the Internet. A second application, the Positioning Serial Client, was written to intercept and collect serial data being sent from the OBE to the external positioning unit. A final application, the Augmentation Parser was written to parse and correlate messages from the OBE Open Services Gateway Initiative (OSGi) log file, the OBE serial log file and the DGPS Proxy log file. The RSE was connected to a server that provided augmentation messages. A vehicle with the augmentation application running was started in the proximity of the RSE. The OBE in the vehicle received the augmentation messages from the RSE and forwarded them to the external GPS unit which then used the information to augment the position. There were a total of four log files that were collected and used to determine the overall latency of the augmentation messages.

Position-2: Controlled Environment Positioning Accuracy

The goal of this test was to determine if a 95% Circular Error Probability (CEP) of less than 1 m could be achieved using low-cost commercial GPS systems.

Two vehicles were used for this phase of the Positioning service test; one vehicle was fitted with External GPS Receiver A, and one was fitted with External GPS Receiver B. Position data was acquired over a five-lap, test run at the Chrysler Tech Center (CTC) vehicle evaluation road, a five mile stretch of Highway 315, and straight and slalom courses at the Darby Dan Airport. The data collected by the OBE system in the vehicle was then compared with the data from the Topcon system (used as a ground truth sensor) to obtain a measure of the overall position accuracy.

Position-3 Internal GPS Fall-back
The goal of this test was to verify that the Positioning service provides position information when only the internal GPS is available, and when augmentation is not available. To perform this test, the setup used for the Position-2 test was used, and the external GPS unit was switched off, thereby forcing the unit to use the internal GPS receiver.

Position-4 Dead Reckoning Fall-back
The goal of this test was to verify that the positioning service provides position based on dead reckoning when no GPS coverage is available, and that a valid position is reported when GPS coverage resumes. To perform this test, the setup used for the Position-2 test was used, and the external GPS antenna was disconnected, thereby rendering both the internal and external GPS units non-functional.

Position-5 Internal GPS Fall-back
The goal of this test was to verify that the Positioning service successfully logs incidences of external GPS hardware failure and recovery. This test was performed as an ancillary part of the Position-3 test.

Position-6 Augmented GPS Accuracy
The goal of this test was to determine how augmented GPS accuracy might change as a function of distance from the augmentation base station. As described below, this test was cancelled because the augmented positioning accuracy was not measurably better than the non-augmented accuracy, so the test would have shown nothing.

4.3.2.1.1 Test Facilities and Equipment

Static testing was conducted in the VII Test Garage Environment at Battelle Memorial Institute in Columbus, OH.

Four locations, representing different environments, were used for the dynamic test phase.
The VII Test Track Environment at the CTC vehicle evaluation road in Auburn Hills, MI, shown in Figure 4-24, and the Darby Dan airstrip west of Columbus Ohio offered controlled, dynamic conditions. Highway 315, in Columbus, OH, and the Michigan DTE were used to evaluate the system against an actual vehicular roadway environment. Each location offered various speed changes and curves. Vehicle traffic, frequent stops, and overpasses were additional variables offered by Highway 315 and the DTE.

Figure 4-24 VII Test Track Environment

Figure 4-25 Topcon Survey System

Figure 4-26 Topcon Antenna Mount on Test Vehicle

Since the tests required knowledge of the absolute position of the vehicles (in order to assess the accuracy of the various elements), a survey grade positioning system was used as a "Truth" sensor. The Topcon GR-3 is a geodetic roving tracking system and combines three satellite position systems: GPS, Global Navigation Satellite System (GLONASS) and the European Galileo system. The Topcon system has a static accuracy of 3 mm and Real-Time Kinetic (RTK) accuracy of 10 mm. The unit is shown attached to the test vehicle in Figure 4-26.

4.3.2.2 Positioning System Test Observations/Findings

GPS Accuracy

Neither Receiver A or B were capable of meeting the expected 1 meter 95% CEP Accuracy. In addition, it was observed that the accuracy varied significantly depending on the characteristics the road (and the resulting vehicle dynamics). The results for these two Receivers taken on the Chrysler Test Track are shown in Figures 4-27 and 4-28.

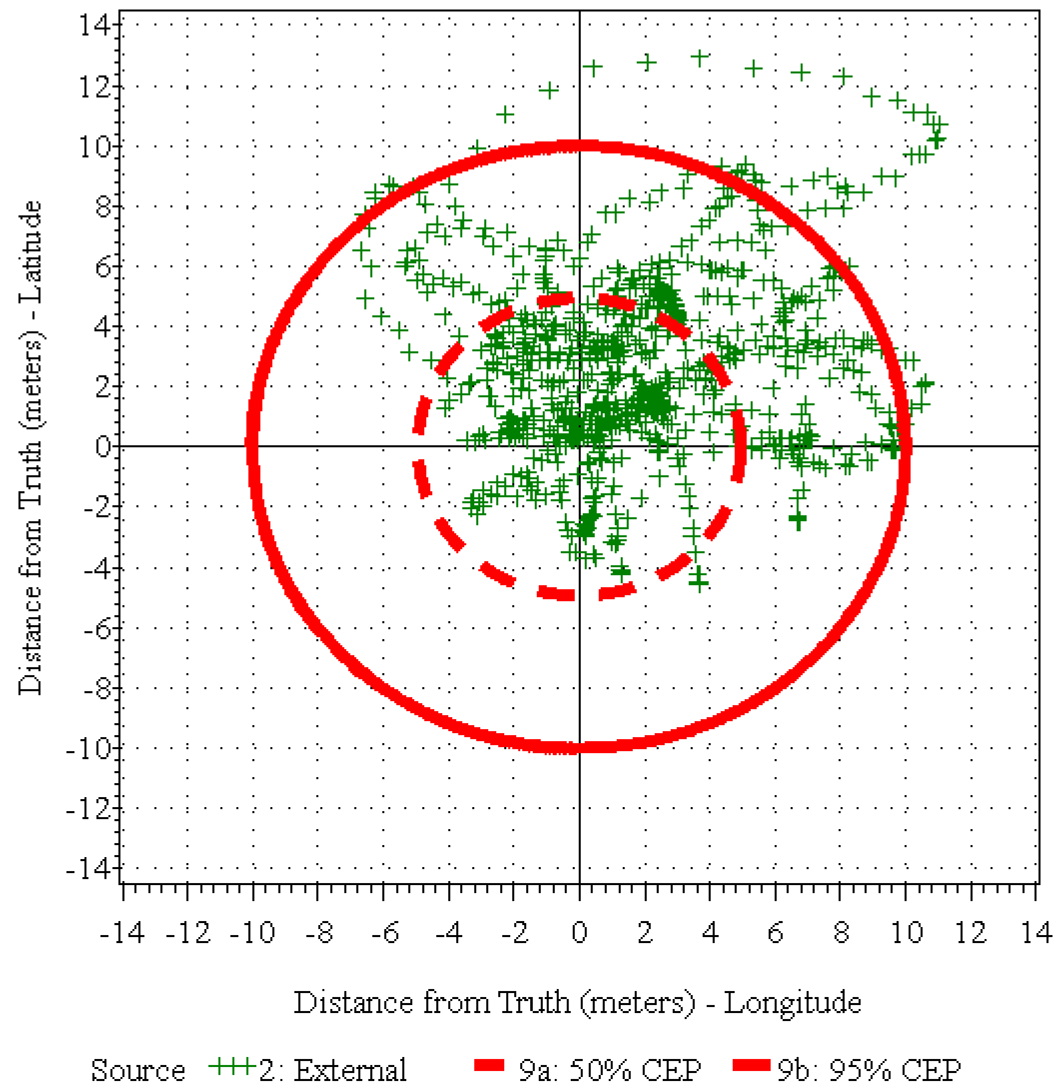


Figure 4-27 Receiver A Positioning Accuracy

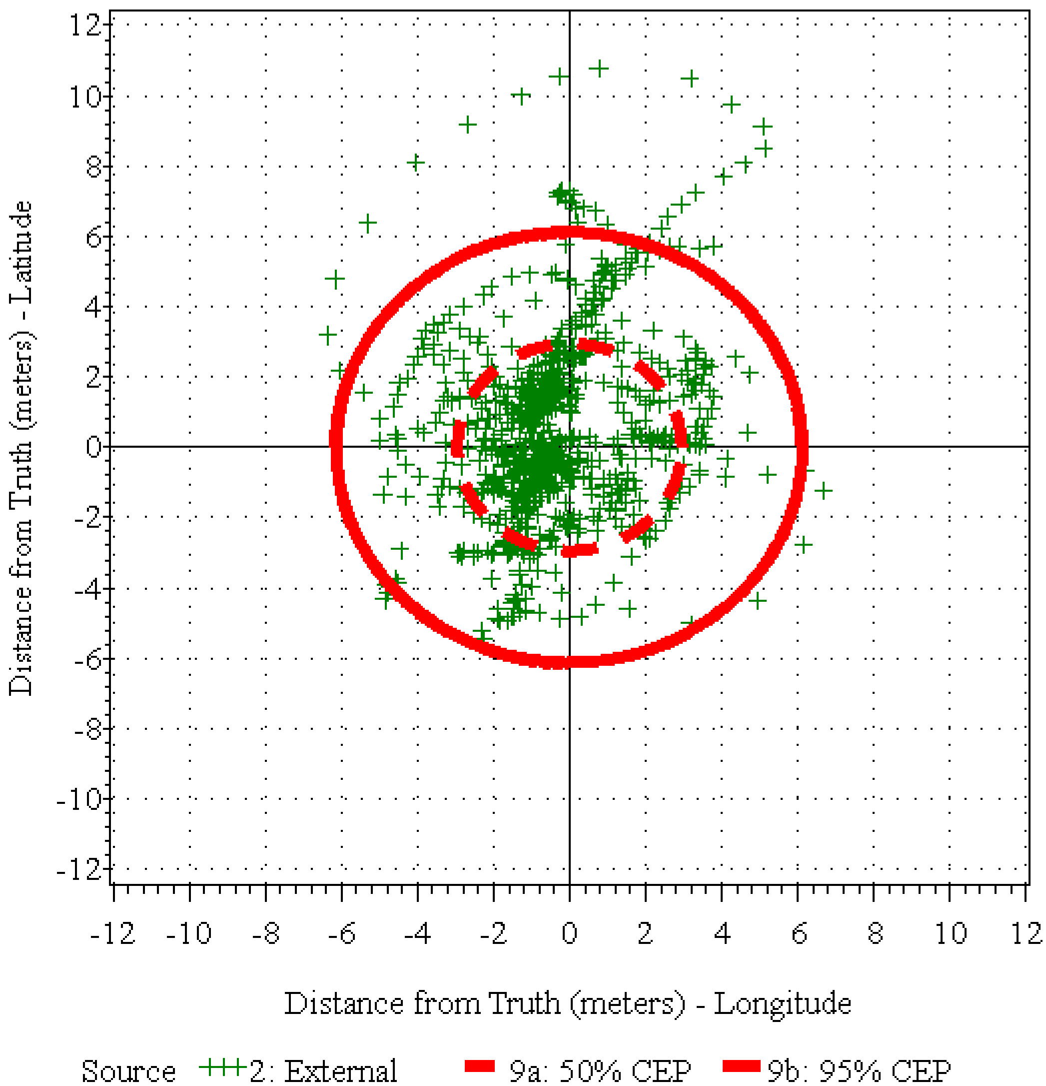


Figure 4-28 Receiver B Positioning Accuracy

The center of these plots represents the zero error point. As can be seen in both plots, the data points are somewhat dispersed around a general main point. The CEP contours are shown in red. The dashed line represents the circle inside of which 90% of the data points lie; the solid line represents the region that contains 95% of the data points. Clearly, under these dynamic conditions neither Receiver is close to the 1 m, 95% accuracy level. Receiver B produced a 95% CEP of 6.13 m, while Receiver A produced a 95% CEP of about 10 m.

Important elements of the data shown in the figures are the loops that appear to show the reported position sweeping or orbiting the main cluster of data points. Extensive post analysis indicates that these loops are a result of the motion of the vehicles around the track. In regions where the trajectory was relatively stable (for example, on straight sections of the road), the data points collect close to the zero error center point. The spread in this region is apparently due to typical GPS error sources including systematic offsets due to atmospheric effects (why the cloud of data is not centered on the origin of the plot), and random GPS receiver clock errors, etc (why the cloud has a finite size). However, in regions of the track where the rate of change in the vehicle's latitude or longitude change sign, meaning that the vehicle has reversed its direction in that axis (latitude or longitude), the system always overshoots. Essentially, the positioning Receiver's mathematical filters cannot adapt to rapid changes in direction in either latitude or longitude.

Further analysis indicates that this issue could be easily solved by filtering latitude and longitude together as a coupled pair of functions rather than independently. Independent treatment of latitude and longitude corresponds to mobile objects that do not follow paths, but wheeled vehicles always follow paths, so if the latitude measurement changes, there is always a corresponding change in either speed (vehicle slowing down or speeding up and not changing direction), or there is a corresponding change in longitude (indicating that the vehicle is changing direction).

Since the loops in Figures 4-27 and 4-28 represent a substantial contribution to the size of the 95% CEP values, it is expected that this sort of improvement would substantially improve the positioning accuracy of these commercial systems.

This observation is further supported by the observation that when a smoothing function available in Receiver B was activated, the loops grew substantially larger, and the 95% CEP increased by 50%. Both Receivers did, however, exhibit sufficient accuracy to differentiate lanes providing the vehicle was traveling in a straight line. This was demonstrated during the Tolling Application.

Effect of Augmentation (GPS Corrections)

The addition of Augmentation (HANDGPS) corrections did not substantially improve position accuracy in either of the Receivers. Receiver A 95% CEP changed by 0.13 m with and without augmentation. In contrast, CEP of Receiver B quadrupled. It is not clear why this occurred, but discussions with both manufacturers indicate that the Receivers have been designed to support commercial requirements and the internal noise contributors are dominant. As a result, the effects of external GPS noise contributions (for example, atmospheric effects) that are typically reduced by external augmentation corrections are overshadowed by these internal noise sources. This makes sense for the observed behavior of Receiver A, but it does not explain the aberrant behavior of Receiver B.

POS-4: Dead reckoning serves to improve accuracy of the basic GPS receiver on straight roads. Tests results indicate a CEP of 2-4 m with 95% confidence level (appears to be due to improved averaging of GPS position fixes).

POS-5: Commercial Wide Area Augmentation System (WAAS) enhanced receiver performed better than embedded units but did not have dead reckoning capability.

POS-6: Used without any GPS inputs, dead reckoning positioning works well (up to about 2 miles).

4.3.3 Security Tests

A systematic set of laboratory and track tests were carried out to assess the functionality and performance of the Security subsystem. As will be discussed in the subsequent sections, the performance tests were hampered by performance issues with the OBE and the OBE test applications. It is not clear at this time, if these performance issues are with the OBE itself, with the OBE applications being used to test the security system, or with the logging functions used to gather data about the system.

Despite these issues, the Security subsystem performed the required functions in all tests.

4.3.3.1 Security Subsystem Test Overview

The VII POC Security service and CM subsystem testing consisted of two phases: a laboratory phase using an OBE and RSE in a stationary laboratory environment and a road test phase carried out on the Chrysler Test Track.

Phase 1 was carried out at a test lab facility at Telcordia. The Phase 1 laboratory tests were:

L1 – WSM Signature Validation Density Test

The objective of this test was to assess the ability of the OBE to receive and successfully process security credentials at high message rates. The approach was to use signed WSM messages sent at regular rates, and then to increase both the transmission rate, and the number of transmitting OBEs, to determine the rate where the receiving OBE processing delay begins to interfere with reception. While the processing speed of the OBE is not a specified requirement (since it depends entirely on the OBE implementation), it was important to assess the impact that processing speed has on the ability of a receiving terminal (OBE) to process signed WSMs. This information can then be used to guide subsequent terminal requirements and development. This test was carried out using five OBEs in a lab environment.

L2a – Revoked Anonymous Certificate

The objective of this test was to confirm that the OBE security system properly rejects messages signed using a revoked certificate. This test requires that the sending RSE or OBE be using certificates that have been revoked, and that the sending unit NOT be connected to the CA. This is necessary because if the sending unit is allowed to contact the CA it will determine that its certificates are revoked, and it will seek to update them. Upon receiving a signed message, the test OBE checks the certificate against a stored Certificate Revocation List (CRL) and if the certificate is listed, it should reject the message. This requires both that the OBE security functions properly check the CRL, and that the OBE Certificate Management functions have the ability to successfully contact the CA over the air and properly download the latest CRL. This test was carried out using two OBEs, one that has been connected to the CA via an RSE prior to the test (to obtain the CRL) and the other which sends messages using a revoked certificate.

L2b – Anonymous Certificate Replacement

The objective of this test was to test the OBE Security subsystem’s ability to determine that its certificates have been revoked, to contact the CA, and to obtain replacement certificates. This process uses the double blind anonymous certification process described in Volume 2a. The test was carried out in a lab environment using a single OBE connected to the CA via an RSE.

L2c – Anonymous Certificate Replacement Denial Test

The objective of this test was to validate that the CA properly denies replacement of certificates for an OBE that has exceeded its re-key limit. In practice, the criterion for re-key denial would be set according to governance policies. For purposes of this test, the re-key limit was arbitrarily set to three re-key cycles. The test was carried out in a lab environment using a single OBE connected to the CA via an RSE.

L4 – IP Encryption Test using Public Key Cryptography Test

The purpose of this test was to validate that the OBE can encrypt and decrypt Internet Protocol (IP) packets using IEEE P1609.2 based public key cryptography. The communications between CM and CA was used as the capture scenario because it uses encrypted IP communications.

L5 – Identified Certificate Expiry and Replacement Test
The objective of this test was to assess the OBE security system's ability to properly determine that its identified certificates had expired, and seek and receive replacement certificates from the CA.

Phase 2 was conducted at the CTC Test Track in Auburn Hills, Michigan. The Phase 2 Track tests were:

T1 – Anonymity Test
The objective of this test was to assess the degree to which the anonymity provisions of the security system design were able to prevent identification and tracking of any individual vehicle through its message transmissions. The approach proposed here was to use multiple OBEs in known positions, and to receive and record multiple message transmissions from each. Then, knowing the actual positions of the OBEs, seek to match received messages with OBEs using only the security and WSM header elements of the messages (that is, not looking at the payloads themselves, since, while stationary, the OBEs would be easy to identify from the payloads which contain vehicle position).

This test was **not performed** due to schedule and technical complexity issues. As this test was better defined, it was found to be very difficult to implement. The OBEs cannot be used as they are designed to receive the messages for this test because the OBE security libraries strip off all security and WSM header information. Therefore, no inherent mechanism in the OBE captured and logged the (security certificate and WSM header) information that was necessary to actually carry out the test. While a DSRC "sniffer" was developed, the security implementation of this was very late. Because of the late availability of the sniffer, and the complexity of the test, it was determined that the test should be deferred to a later time. Because the security system is designed to prevent identification and tracking of OBEs, this test is extremely difficult to carry out. Rather than rush the test with limited time, limited resources and a limited number of OBEs, the consensus of the team was to defer it to some time when it can be more accurately and completely carried out.

T2 – Dynamic CRL Test
The objective of this test was to determine the performance envelope of the CRL delivery function. Specifically, the goal was to determine the size of the CRL that could be delivered to an OBE in a single RSE encounter. To perform this test, CRLs of various sizes were created, and the OBE was driven past the RSE at various speeds. The OBE speed and the size of the CRL were gradually increased until the system was unable to completely transfer the CRL in a single pass through the RSE footprint. This test was carried out using an OBE equipped vehicle and an RSE on the CTC Test Track facility.

T3 – Dynamic Re-key Test
The objective of this test was to determine the performance envelope of the anonymous certificate replacement function. This was seen as the limiting case since, to maintain anonymity, the security subsystem associates multiple certificates to an anonymous OBE application as compared to a single identified certificate for a non-anonymous (identified) application. Specifically, the goal was to test whether a full set of anonymous certificates could be delivered to an OBE in a single RSE encounter at various vehicle speeds. This test was carried out using an OBE-equipped vehicle and an RSE on the CTC Test Track facility.

T4 – Geographic Scope Test
The object of this test was to verify that signed RSE messages are only accepted by the OBE when the RSE transmitting location is 1) within the RSE's signed location tolerance, and, 2) within the location tolerance of the OBE. The main goal of this test case is to verify that the OBE can check if messages (WSAs and WSMs) it receives from a stationary RSE are valid, based on the geographic information contained in the message signatures. The geographic information is carried in the digital certificate used by the RSE to sign WSAs and WSMs. It is used to inform the vehicle of the geographic area within which the RSE is authorized to provide services. If the vehicle determines that received messages have not originated from RSE operating within the geographic region for which it is authorized, it will not accept the messages. For rejected WSAs, it will not join the Wave Basic Service Set (WBSS) offered by the RSE, and for WSMs it will simply ignore the message. This check is designed to protect OBEs against incorrectly located or "rogue" RSEs. This test was carried out by positioning an RSE on the test track and sending out a WSA with a signature location element different from the actual location of the RSE. To do this the RSE management functions had to be fooled into thinking that the RSE was located in a different place. An OBE was then driven past the RSE, and the receipt and rejection of WSAs was recorded. This test was carried out using an OBE-equipped vehicle and an RSE on the CTC Test Track facility.

T5 – V-HIP Security Test
The objective of this test was to assess the ability of the system to successfully encrypt data sent over the network using the VII-Host Identity Protocol (V-HIP). The V-HIP protocol was developed to allow OBEs to anonymously re-establish IP sessions from one RSE to the next. This subsystem was **not tested** in the security tests because the Transaction Service Manager (See Volume 2A) was not configured to support the IEEE P1609.2 security functions.

4.3.3.2 Security Test Facility

The Security subsystem tests were carried out using a combination of laboratory facilities and a road test track. These are described in the following sections.

4.3.3.2.1 Phase 1 Laboratory Test Environment

The Phase 1 laboratory tests were carried out in a laboratory facility at Telcordia. This setup, shown in Figure 4-29, consisted of a single RSE and five OBEs. Each OBE was equipped with its own dual antenna to receive GPS signals and DSRC Radio signals. Each OBE was connected to an Internet Protocol version 4 (IPv4) switch which was used for remote account access and to configure the OSGi framework using the mConsole client from a laptop connected to the local network.

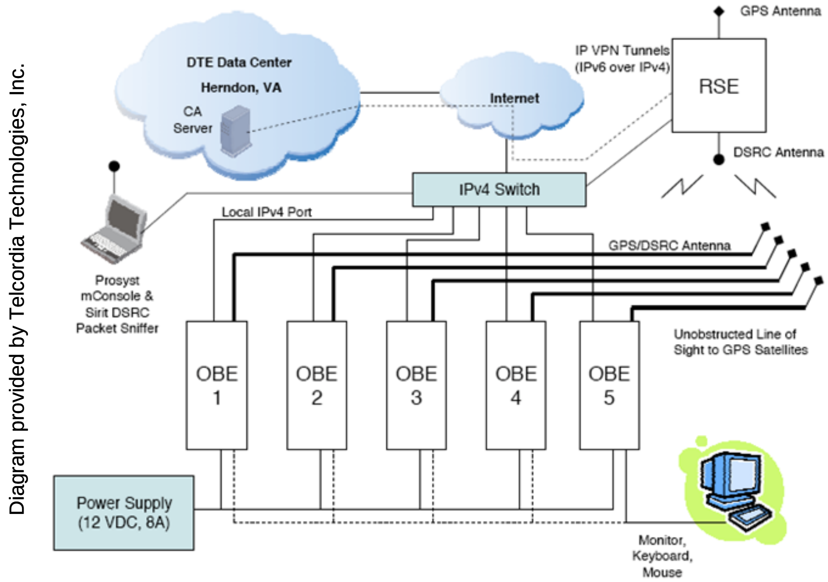


Figure 4-29 Phase 1 Laboratory Security Test Setup

The RSE was also connected to the IPv4 switch, which provided Internet connectivity to support communications with the CA located in the DTE data center in Herndon, VA.

4.3.3.2.2 Phase 2 Track Security Test Environment

In Phase 2, testing was conducted on a closed test track with multiple RSEs that were linked to the VII data center infrastructure located in Herndon, VA. The tests in this phase required the full geographic footprint of the RSE and required vehicles with OBEs to be traveling through one or more RSE zones.

The testing was conducted at the CTC Track in Auburn Hills, MI. An aerial photo of the facility is provided in Figure 4-30. Three general locations for RSE positions are indicated in the photo by yellow markers.

Figure 4-30 Phase 2 Track Security Test Environment

4.3.3.2.3 Security Test Data Capture

OBE log files and a packet sniffer were used to collect data for analysis. Specifically, the OSGi log files were used to collect data generated by the Heartbeat Application, which uses the OSGi Log service to record the ID, send time (or receive time), and payload of each Heartbeat message it sent (or received). The security library, which signs outgoing Heartbeat messages and verifies the signatures of incoming Heartbeat messages, uses the log service of the underlying operating system to record the status of crypto operations. Custom tools were developed to read the log files, parse log entries, perform data analysis and generate results.

A DSRC packet sniffer was used to inspect the WSM and IP messages exchanged between OBEs and between OBEs and the RSE.

4.3.3.3 Security Subsystem Test Results and Findings

4.3.3.3.1 Security Subsystem Test Results Overview

The VII Security is a complex system that consists of many components from many suppliers to the VIIC. These security components need to be properly integrated, and the security functions also need to be integrated with the applications. By its very nature, the security system is intended to prevent system operation under many unusual situations. As a result of this complexity, and the rather late development of the security functions, the tests were hampered by system integration issues. Because of the many dependencies, some of the security software could not be fully tested prior to integration as a complete system, so the initial security testing work included an unexpected level of security system integration and code revision.

Despite these road blocks most of the security functions were successfully tested. This included:

- Signing and verification of WSAs, signing and verification of WSMs
- Acquisition and use of IEEE P1609.2 certificates
- Dynamic downloading of CRLs for certificate verification
- Dynamic OBE re-keying
- IP encryption
- Geographic scope verification

Without question, this represents a substantial and tangible achievement of the VII program and the Security WO.

4.3.3.3.2 Security Subsystem Test Findings

The overall Security test results are summarized in Table 5.

Test Case	Overall Test Result
L1 – WSM Signature Validation Density Test Verify ability to receive and process security credentials at high message rates.	Partly Successful: Functions successfully at tested rates, but high stress results difficult to interpret due to high latency and irregularity in Heartbeat transmission and reception. OBE was unable to operate at high enough heartbeat rates to stress the ability to perform high-speed message validation operations.
L2a – Revoked Anonymous Certificate Test Verify ability of the system to reject messages signed using a revoked certificate.	Successful: The OBE CM was able to successfully receive CRLs from the CA and correctly process the CRLs. Furthermore, OBEs successfully ignored Heartbeat WSMs signed with revoked certificates.
L2b – Anonymous Certificate Replacement Test Verify ability to detect revoked/expired anonymous certificates and apply for replacements.	Successful: The OBE CM was able to successfully replace all revoked certificates in a received CRL. Furthermore, the Heartbeat application successfully used the replacement certificates to sign Heartbeat WSMs.
L2c – Anonymous Certificate Replacement Denial Test Verify ability to detect that the re-key limit has been exceeded.	Successful: The CA successfully kept track of the frequency of re-key requests from each OBE and successfully denied re-key requests from an OBE after a re-key threshold had been reached.
L4 – IP Encryption Test using Public Key Cryptography Test Verify ability to encrypt and decrypt IP packets.	Successful: The end-to-end communication between an OBE and the CA connected to the backend infrastructure was successfully encrypted. The plain text content of the communication was invisible in the captured IP packets. The encrypted contents were successfully decrypted by the CA.
L5 – Identified Certificate Expiry and Replacement Test Verify ability to detect expiration of identified certificates and ability to get replacements.	Successful: The OBE CM successfully detected expired certificates for Toll Payment and a test application on the OBE and then successfully requested replacement certificates from the CA in the VII infrastructure and successfully installed the new certificates on the OBE.
T1 – Anonymity Test Verify ability to prevent identification and tracking.	Not Tested.
T2 – Dynamic CRL Test Determine practical size of CRL download at a single RSE encounter.	Successful: The OBE CM was able to successfully download and process CRLs of various sizes in various driving conditions, but exhibited high CPU utilization for very large CRLs. CRLs of up to 30 K entries were transferred in a single RSE encounter at 65 mph.
T3 – Dynamic Re-key Test Verify ability to download a full set of anonymous certificates at speed.	Successful: The OBE CM was able to successfully detect revoked certificates and replace them with new certificates within a single RSE radio coverage zone, by making re-key requests to the IEEE P1609.2 CA in the VII infrastructure under various driving conditions.

T4 – Geographic Scope Test Verify that signed RSE messages are only accepted by the OBE within defined geographic boundaries.	Successful: The geographic scope feature functions properly, rejecting messages outside the geographic scope, but positioning inaccuracies create occasional anomalies.
T5 – V-HIP Security Test Verify ability to encrypt data over the network using HIP.	Not Tested. Security functions unavailable at Transaction Service Manager (TSM).

Table 4 Security Test Results Summary

4.3.3.3.3 Security Subsystem Test Anomalies

While the overall Security testing proved the basic operation of the system, a number of important shortcomings were also observed.

Test Case L1 (WSM Signature Validation Density Test) which assessed the latency in the OBE's ability to send, receive and validate signed WSMs at various message rates using the Heartbeat Application, showed that the Heartbeat Application performed poorly with substantially lower than expected throughput, high latencies, lost messages and out of order messages. Because these latencies and out of order messages were also observed with the security functions disabled, it does not appear that the security processing added any significant delay. However, the uncertainty arising from these behaviors prevents drawing a final conclusion.

Test Case T1 (WSM Anonymity Test) had to be curtailed in light of extra budget spent on security integration and regression testing and the fact that the Packet Sniffer with the capabilities needed to conduct Test T1 was not available at the time of track testing. Such a version of the Packet Sniffer eventually became available, but too late to support any analysis under the current task.

Test Case T2 (Dynamic CRL Test) demonstrated successful CRL downloads, but there is a high CPU utilization issue with very large CRLs. It is unclear if this CPU utilization issue is simply a product of limited OBE processing power, or if it is due to other inefficiencies in the software implementation.

Test Case T4 (Geographic Scope Test) demonstrated successful position security checks, but the position accuracy was, in some cases insufficient to provide accurate geographic scope behavior (at the edges of the scope region). In addition, Secure Signage, which was the intended application for Test T4, failed to function at the test track, and the OBE CM had to be used as a testing application instead.

Test Case T5 (V-HIP Security Test) was not conducted because a security library implementation could not be provided to operate on the network side Transaction Service Manager within the timing and budget constraints of the program. As a result, there was no point in also configuring the OBE Communications Manager (OCM) to support security during HIP operation.

4.3.4 Advisory Message Service Tests

The purpose of this test phase is to verify that the integrated VII POC zystem is capable of supporting advisory message delivery and display. In this test, the VII POC system supports the delivery of advisory messages from network users to vehicle drivers based upon location and situation relevant information. Messages are prioritized both for delivery and presentation based on the type of the advisory, and the location of the vehicle. These messages may be in the form of text, graphics, or audio cues presented by the generic vehicle HMI used in the OBE.

4.3.4.1 Advisory Message Service Test Description

This test evaluated how well signage data, which originates from either the public or private Network User Component (NUC) of the VII Service Delivery Node (SDN), is transmitted via Advisory Message Delivery Service (AMDS) of the RSE and processed by the OBE.

AMS-1: Single Advisory Message Per RSE Transmitted to OBE
The objective of this test was to assess the performance of the advisory message system in the simple case where a single vehicle receives a single advisory message at each RSE used in the test. The messages are saved, and then presented to the driver within the geographic region associated with the message.

Five different advisory message types were used in this test: two CCH messages and three SCH messages. The vehicle was driven past RSEs, one at a time, at 55 to 70 mph in the DTE. The locations where the messages were received, where they were initially displayed and where the displayed messages were removed, were recorded.

AMS-2: Multiple Advisory Messages Per RSE Transmitted to OBE
The objective of this test was to assess the performance of the advisory message system in the more complex case where a single vehicle receives a multiple advisory messages, in some cases on different channels, at each RSE used in the test. The messages are saved, and then presented to the driver within the geographic region associated with the message.

Ten different advisory message types were used in this test: four CCH messages and six SCH messages. Two RSEs messages were sent on both the CCH and on the SCH.

As in the first test, the vehicle was driven past RSEs, one at a time, at 55 to 70 mph in the DTE. The locations where the messages were received, where they were initially displayed and where the displayed messages were removed, were recorded.

AMS-3: Message Duplicate and Message Update Processing
The objective of this test is to assess the ability of the system to properly handle duplicate messages and updates to messages already received.

Advisory messages contain various components that allow the Signage Message Application to determine if an incoming message is new, if it has already been received or if it is an update to a message received earlier. If the message is new, it is saved and used when its display information indicates that it is relevant. If the message is a duplicate, then it is simply discarded. If it is an update, then saved content of the previous version is overwritten.

By sending the same messages from different RSEs, the objective was to assess these three different ways of handling incoming messages.

Test Setup

Testing was conducted on public roadways under existing field and traffic conditions in the DTC. Figure 4-31 provides a summary map of the test route and locations of the RSEs.

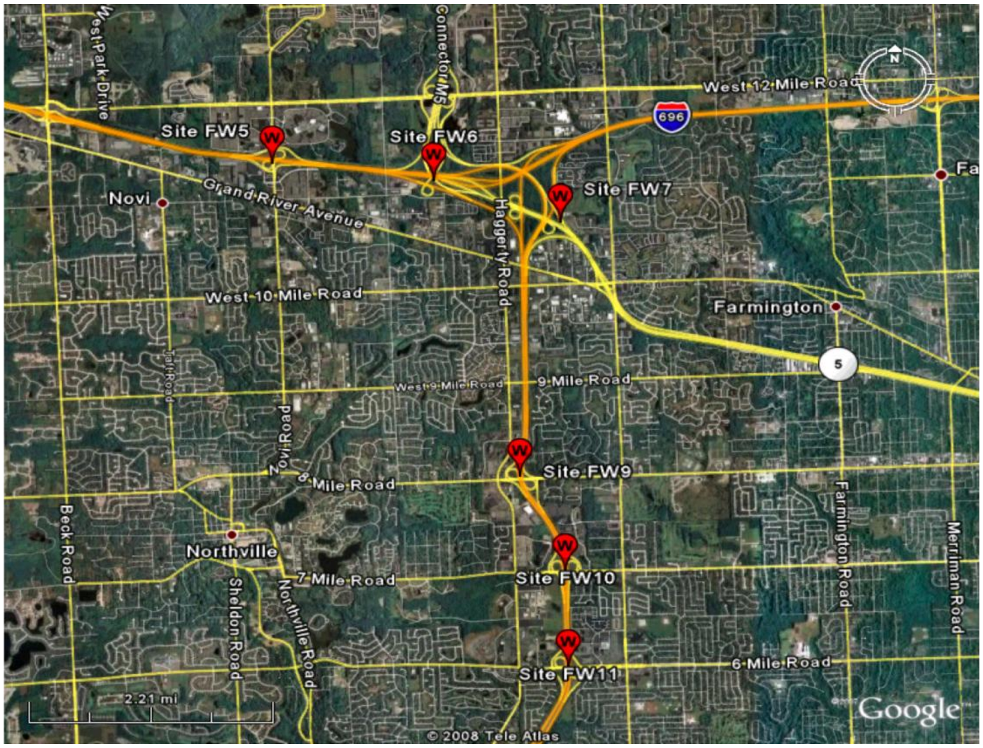


Figure 4-31 Advisory Message Test Route

4.3.4.2 Advisory Message Test Observations and Results

Advisory Message Service operations were observed during testing of the Signage Application in the DTE. Findings from the tests are detailed below.

During the tests, all signs displayed as intended (as shown in Table 6) with most signs appearing within the specified 30 m of the beginning of the activation region.

Test Case	Test Duration (Minutes)	# Sign IDs	# Regions Crossed	# Valid Displays	% Valid Displays
1a: Opposing Directions Of Travel (1 sign/RSE)	143.18	5	133	133	100%
1b: Bumper-2-Bumper (1 sign/RSE)	100.30	5	130	130	100%
2a: Opposing Directions (2 sign/RSE)	93.9	9	242	242	100%
2b: Bumper-2-	98.6	9	238	238	100%

Bumper (2 sign/RSE)					
3a: Opposing Directions (2 sign/ 2 RSE)	83.4	8	207	207	100%
3b: Bumper-2-Bumper (2 sign/ 2 RSE)	75.6	4	114	114	100%

Table 5 Advisory Message Test Results Summary

Most AMDS messages were received numerous times (often hundreds of times). While this message redundancy assures near 100% delivery, it is not efficient.

There were several instances noted (See Table 7) where signs were displayed outside the specified 30 m from the activation region. This appears to be a result of latency in the OBE either resulting in late notification of the crossing of the region threshold, or late logging of the event. However, with one exception attributable to test error, these anomalies were minor.

Test Case	**Test Duration (Minutes)**	**# Sign IDs**	**# Displayed/ Removed Within 30 Meters (Average)**	**# Displayed/ Removed Within 30 Meters (Average)**
1a: Opposing Directions (1 sign/RSE)	143.18	5	127 (14.35 m)	95.5%
1b: Bumper-2-Bumper (1 sign/RSE)	100.30	5	122 (15.62 m)	93.8%
2a: Opposing Directions (2 sign/RSE)	93.9	9	228 (23.13 m)	94.2%
2b: Bumper-2-Bumper (2 sign/RSE)	98.6	9	228 (14.00 m)	95.8%
3a: Opposing Directions (2 sign/ 2 RSE)	83.4	8	165 (103.65m)*	79.7%
3b: Bumper-2-Bumper (2 sign/ 2 RSE)	75.6	4	114 (11.00 m)	100%

*Appears to be a test setup problem

Table 6 **Advisory Message Removal Test Results Summary**

4.3.4.3 Advisory System Test Anomalies:

In general, the Advisory Message tests demonstrated that the application works well with all messages displayed, even under conditions of imperfect communication. The tests demonstrated the ability to deliver the signs according to their prioritization and according to the location and heading of the vehicle. However, during the initial integration several observations were made that have an important impact on the operation of this system. These are described below.

CCH messages included in WSA (messages advertised as being on SCH, but present only on CCH) confuse the system. The RSE Playlist setup process needs to be refined to prevent this situation.

Time relevance (OBE timeout) and Lifetime (RSE timeout) were not adequately defined or tested. It is unclear exactly what circumstances should make a message disappear from an RSE. The method defined in Society of Automotive Engineers (SAE) J2735 for message ID and timing appears to be overly complex and somewhat redundant.

The approach used to define and use directionality for messages is incorrect. The current approach is unnecessarily sensitive to variations in heading caused by measurement errors and road variations. The approach needs to be based on actual direction of road, not vehicle heading (e.g. “northbound” versus “north”).

The approach using polygons to define activation regions is prone to errors and ambiguities. A simpler and more robust approach to directionality and activation criteria definition is needed.

The HMI prioritization scheme is complex and results in confusing system operation at times. This causes the system to be very difficult to configure properly.

It was observed several times that updates to signage messages in the network were not reflected in the RSE Playlists. Sometimes, several tries were needed to get a message update to show up at the RSE.

4.3.5 Probe Data Service

The PDS performance was tested under a variety of vehicle conditions. This test included verifying the system’s ability to collect and transmit three types of probe data: Periodic Event Based, Start/Stop snapshots according to configurable capture and transmit policies specified by network-side application. The Probe Data Application formats the data and passes the snapshots to the PDC system at the SDN whenever the vehicle has DSRC connectivity that advertises the Probe Data Collection Service (PDCS).

4.3.5.1 Probe Data Test Overview

The PDS test was based on four test cases described below.

Probe-1 Single Vehicle Data Collection and Upload
This was a baseline test aimed at determining the ability of the system to collect probe data from a single vehicle in a single RSE encounter. In this test, a vehicle was driven around a section of the DTE where it collected probe data snapshots and, upon encountering an RSE, sent the snapshots to the PDC system.

Probe -2 Two Vehicle Data Collection and Upload
The objective of this test was to assess the ability of the system to support uploads of probe data at a single RSE when two probe vehicles were present. This test was compromised by the fact that during development of the probe data security system, known as VII Datagram Transport

Layer Security (V-DTLS), it was found that the Internet DTLS standard on which V-DTLS is based, was unable to handle multiple parallel threads. The program schedule did not allow time to revise the DTLS implementation to support multiple parallel threads. As a result the test merely assessed the ability of the system to support two consecutive downloads, each equivalent to Probe-1. The inherent limitation of the V-DTLS system thus did not allow the assessment of overall probe data throughput, because the data link was artificially limited to a single vehicle at a time.

In this test, two vehicles were driven through a section of the DTE where they collected probe data snapshots and, upon encountering an RSE, sent the snapshots to the PDC system.

Probe-3: Large Upload, Two Vehicles
The objective of this test was to assess the system ability to support multiple large data uploads. This test case was similar to Probe-2 Test Case, but differed in that the maximum size of the snapshot buffer for each vehicle was increased from 30 snapshots to 300 snapshots. Only a single buffer was utilized to capture all three types of snapshots; periodic, start/stop, and event-triggered. As with Probe-2, this test was inhibited by the single thread ability of V-DTLS.

Probe- 4: Probe Data Management
The objective of this test was to determine if it was possible to adjust the PDC parameters on the fly, through directives transmitted from the infrastructure PDC system. Test Case Probe-4 focused on assessing whether Probe Data Management (PDM) messages could be received by the OBE and whether the receipt of these directives impacted the ability of the Probe Data Generation application to generate and transmit snapshots. The vehicles were separated through the test route to limit one RSE interaction per vehicle.

Test Setup
The probe data test was performed at the Michigan DTE. A defined route was selected to allow the vehicle to interact with several RSEs during normal driving conditions (See Figure 4-32). The arrows indicate the route and the red dots represent RSE locations.

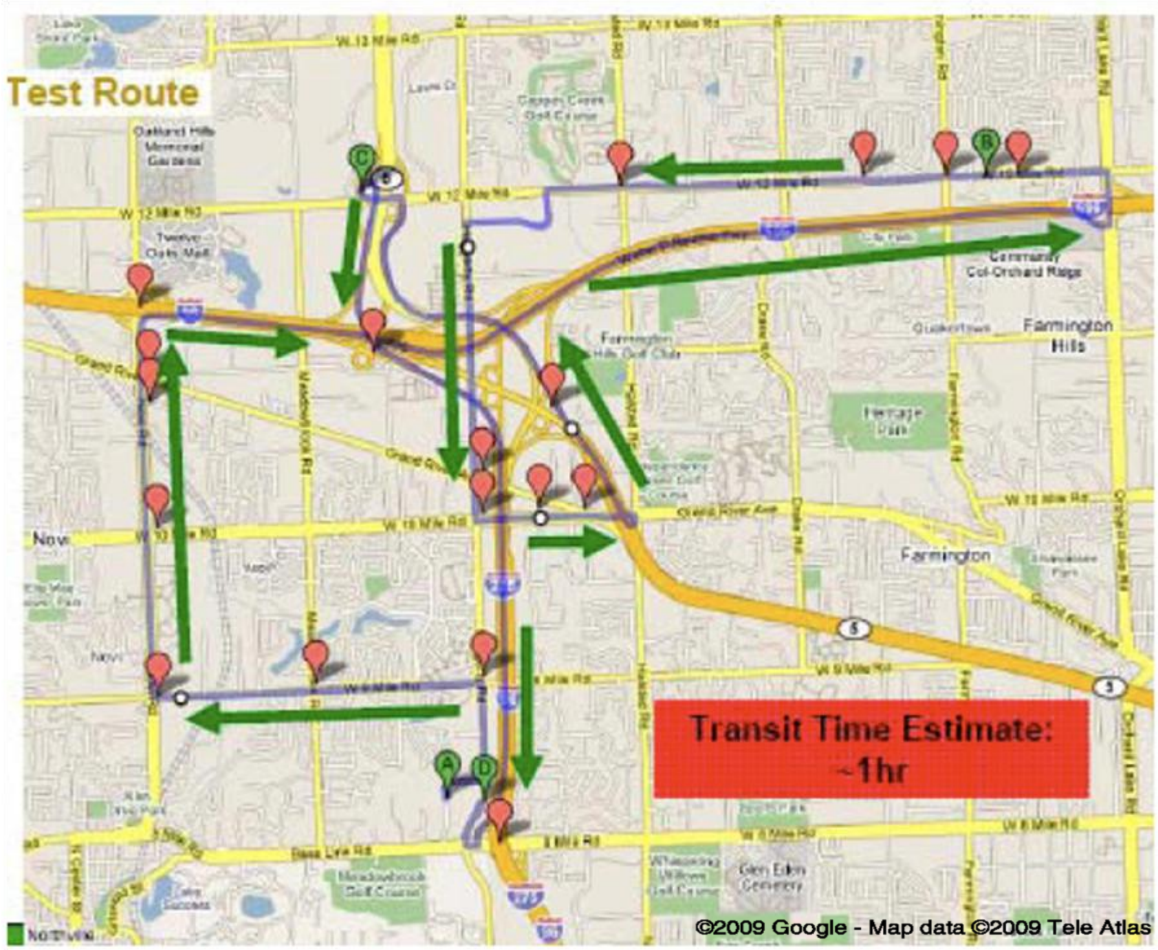


Figure 4-32 Probe Data Test Route

4.3.5.2 Probe Data Service Test Observations/Findings

PDC Efficiency
This test was performed with two different cars each with a single snapshot buffer set to 30 snapshots. Table 7 contains a summary of the results reported after the analysis of the OSGi and SDN logs.

Result	Vehicle 1	Vehicle 2	Total
Number of Interactions	56	28	84
Number of Interactions where V-DTLS Connected (Percentage of Interactions)	47 (83.9%)	26 (92.9%)	73 (86.9%)
Number of Interactions where the Buffer was Emptied (a measure of the number of interactions where the privacy requirements and RSE disconnects that resulted did not truncate the data transfer)	33 (58.9%)	15 (53.6%)	48 (57.1%)
Number of Snapshots in Buffer at Start of Interaction	655	427	1082
Number of Snapshots sent to RSE (Percentage of Snapshots in Buffer Sent)	563 (86.0%)	404 (94.6%)	967 (89.4%)
Number of Snapshots Received at SDN (Percentage of Snapshots Sent that were Received)	535 (95.0%)	373 (92.3%)	908 (93.9%)

Table 7 Probe Test Results

This table shows that 50% to 60% of the RSE interactions resulted in complete data transfer (the entire contents of the buffer were sent). This implies that 40% to 50% of the interactions resulted in an incomplete transfer because the connection was lost before all data was sent, and the remaining data was (correctly) deleted.

Of the snapshots that were supposed to be sent, about 94% were received at the network side of the Probe Data system. While this is slightly lower than the objective of 95%, it is reasonably successful given the developmental nature of the system.

It is clear, however, that more test data is needed to more fully characterize the complex behavior of the Probe Data Application. For example, it might be informative to be able to turn off the privacy safeguards and assess the basic transfer capability of the system, and it would be very helpful to stabilize the behavior of the RSE connections to eliminate rapid connect/disconnect cycles and run the tests again.

Probe Snapshot Generation Frequency Variation

A second element of the Probe-1 Test was to assess the stability of the Probe Snapshot generation rate. The requirements for the POC define the following criteria for PDC timing:

- If speed is ≤ 20 mph then time between snapshots is four seconds
- If speed is ≥ 60 mph then time between snapshots is 20 seconds
- If speed is > 20 mph and < 60 mph, then the time between snapshots is linearly interpolated between four seconds and 20 seconds.

This collection timing was successfully implemented by the Probe Data Application. The figure 4-33 shows data collection frequency as the test vehicle accelerated from a stop to over 60 mph. For the period while the vehicle was traveling below 20 mph, the figure shows a large number of points taken at four second intervals. Once the vehicle passes the 20 mph speed point, the samples are spread more or less evenly at increasing intervals up to 20 seconds. Again, at the 20 second interval, the figure shows a large number of samples indicating that for the period where the vehicle was traveling faster than 60 mph, the system was collecting samples at 20 second intervals.

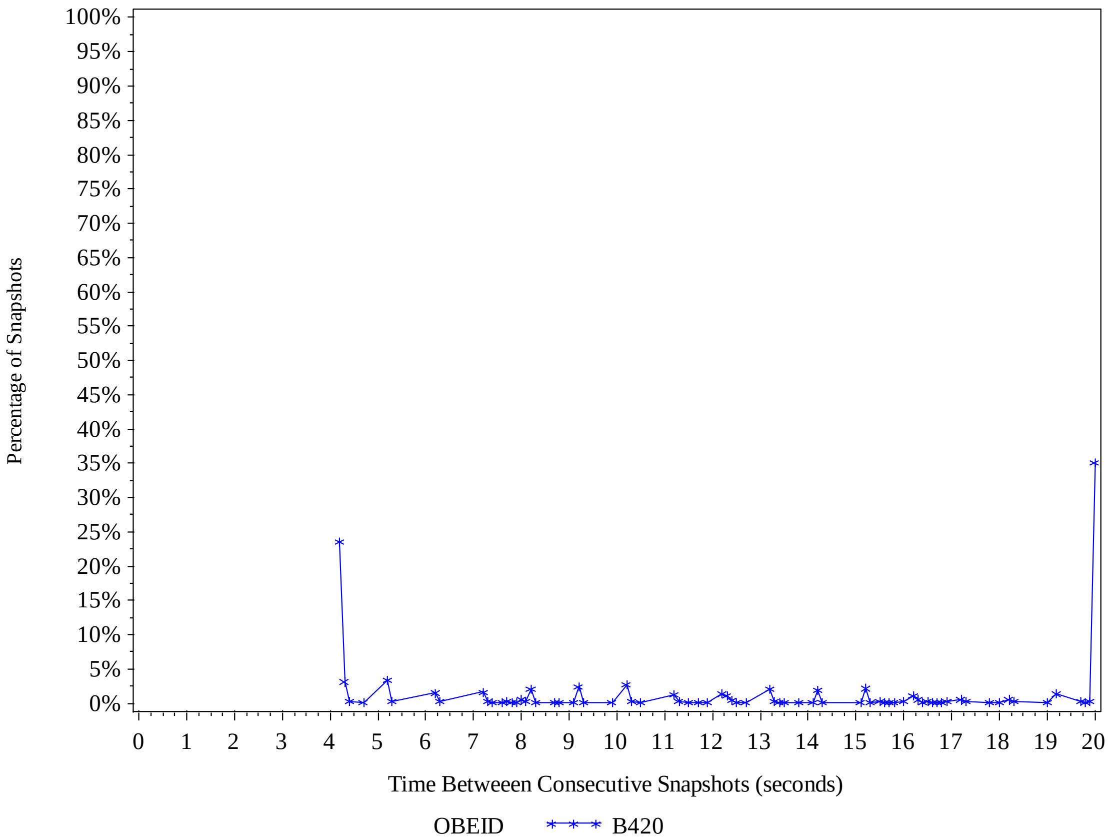


Figure 4-33 Snapshot Generation Interval

Multiple Vehicles

The addition of a second vehicle in concurrence with the first greatly reduced the probe system performance. This appears to be primarily due to the single-threaded nature of the V-DTLS connection (only one vehicle can establish a V-DTLS connection at a time). Further testing and evaluation would be needed with a multi-threaded V-DTLS to accurately measure performance when multiple vehicles can establish a handshake with the RSE and upload data concurrently. An alternative would be to repeat the test without the use of V-DTLS, but with both vehicles stationary and well within the range of the RSE.

Effect of Buffer Size

Large buffers do not cause any significant reduction in probe data delivery efficiency. While the Probe-2 and Probe-3 tests were hampered by the use of two vehicles when V-DTLS is only able to handle a single vehicle at a time, a comparison of the results from the two tests indicates that large buffers do not have a significant impact on the ability of the system to deliver probe data (See Table 8).

	Number of Snapshots Received at SDN (Percentage of Snapshots Sent that were Received)			
	Vehicle 1	**Vehicle 2**	**Vehicle 3**	**Total**
Buffer=30	**526 (90.4%)**	**271 (96.8%)**	**841 (96.1%)**	**1638 (94.3%)**
Buffer=300	**1264 (94.8%)**	**1924 (98.4%)**	**373 (95.3%)**	**3561 (96.1%)**

Table 8 Probe Data Overall Performance

Probe Data Losses

Probe collection and privacy rules cause significant loss of probe data when the DSRC link fails, for example, at long ranges. Current rules require data to be deleted, and not re-sent to protect privacy, and since the system is apparently unable to determine that it has rejoined the same RSE, it deletes unsent data following a lost connection, and thus fails to continue sending it when it reconnects. This results in unusually low overall probe data delivery statistics, but it does represent correct system behavior (the system is properly responding to failed RSE links). For a single vehicle at a single RSE (Probe-1 Test Case) the resulting overall probe data delivery efficiency (data collected vs. data delivered) averages 83.9%, while the transfer efficiency (data sent vs. data delivered) was about 94%. This implies that about 10% of the collected data is lost due to privacy requirements. It is likely that improvements in the stability of the DSRC connection, and improvements in the OBE subsystem’s ability to recognize that it is reconnecting to the same RSE (essentially improving the sophistication of the connection process) would have a positive impact on the overall efficiency of the probe data system.

The results regarding the percentage of snapshots that were not successfully received at the SDN (about 6% of all sent snapshots), suggests that once a secure V-DTLS handshake and connection are established, snapshots are received and transmitted to the SDN with relatively little loss. This is important in that it verifies the solidness of the inherent infrastructure, components as well as demonstrating that the use of DSRC communication to transmit probe information from OBEs to RSEs can be accomplished, provided a connection can be made and sustained. The length of time the vehicle stays in range of the RSE has an impact on a successful V-DTLS connection. This too is an important finding as it suggests that it is not sufficient for an OBE to merely “cross-paths” with an RSE for an upload to occur. Rather, the interaction time for an OBE/RSE needs to be of sufficient length to allow for the establishment of the V-DTLS connection. It might, and usually did, take the OBE/RSE several attempts to make this connection. Although the establishment of a V-DTLS connection is a prerequisite for communications, that alone did not guarantee success. A significant number of instances were observed were a V-DTLS connection was established, but no snapshots were sent, which could be due to a variety of reasons including the termination of the connection due to environmental factors.

Probe Data Management Issues

Tests of the PDM system were initially inconclusive. In general, the system did not perform reliably when sending PDM directives (to change the PDC rate, for example). Of the PDM messages sent, when a vehicle was in range of an RSE, less than 5% were actually received. The reasons for this are not clear, but are assumed to be an improper system setup. Later tests conducted by BAH as part of their public applications testing showed PDM to work well. The PDM system was able to receive directives from a requester, transmit them to OBEs and the OBEs then responded by changing their probe collection parameters as defined in the PDM messages. These results are reported in Volume 3b provided by BAH.

Probe Data Test Anomalies

There were several anomalies observed during the test and/or during the analysis of the test results. These are discussed below.

Definition of "Successful" Probe Data Transfer

The Probe Data system operates under a complex suite of constraints. As a result, it is possible to successfully deliver probe data without delivering all of the data collected in the vehicle. This paradox arises from the privacy constraints imposed on the probe system. The Probe Data Application is required for privacy reasons to only send data belonging to a probe data set (as referenced by a common Probe Sequence Number (PSN)) at a single RSE. This is intended to deny the opportunity to track a vehicle as it moves from RSE to RSE, based on probe data from the same set being sent at more than one RSE. Unfortunately, the current DSRC Radio implementation does not appear to differentiate between RSEs, so the Probe Data Application treats each RSE connection as a "new" RSE. Each time the RSE connection is lost within the nominal footprint of the same RSE, all data that has been collected under a given PSN must be deleted.

This makes the determination of "successful" probe collection very complex, because a successful sequence may not include all snapshots taken.

The initial approach to measuring successful collection events was to measure the number of snapshots in the probe data buffer and to measure the number of snapshots delivered to the probe data system in any given RSE encounter. The RSE encounter was defined as the period between which the RSE is listed as "Available" and "Unavailable" by the OCM. However, it was observed that the Available/Unavailable events occur frequently when the vehicle is within DSRC range of an RSE. Based upon other tests, this behavior was determined to be a function of the OBE radio timeout settings, shortcomings in the DSRC standard and resultant limitations in the radio implementation.

Other methods to define suitable measurement points were also tried, although none of these adequately captures the proper performance, because they fail to properly account for the conflicting requirements of collecting and sending data, and also intentionally deleting data under some circumstances. In the end, the most telling performance measure of the Probe Data system is the ability to deliver "data that was supposed to be delivered". This can be simply defined as the ratio of packets submitted by the Probe Data Application for transmission by the OBE that actually arrive at the network side Probe Data system. This metric measures the aggregate reliability of DSRC and the subsequent network to collect and process probe data messages.

Probe Data Generation Integration with V-DTLS

Another anomaly noted during the analysis of the test was the lack of complete integration of V-DTLS into the Probe Data Generation Application. During these tests, the PDS on the OBE removed snapshots from the buffer to assemble a V-DTLS message as soon as it received an indication that an RSE was available (e.g., the Communications Manager reports to the PDS, that it is in-range of an RSE and provides the PDS with a valid IP address and RSE MAC Address). However, this indication by the Communications Manager does not guarantee a valid V-DTLS connection as the V-DTLS connection is established after the initial link is established. As a result, the snapshots that are pulled from the PDS OBE snapshot buffer(s) are discarded by the PDS Application, if the OBE cannot establish or maintain a V-DTLS connection to the RSE for a duration that ensures all snapshots are sent.

4.3.6 Heartbeat Service

The Heartbeat Application was designed to test the basic capability of sending messages from V2V in order to indicate whether or not the system would be capable of supporting cooperative vehicle safety applications. This testing was conducted under both open road situations and under conditions where the line of sight between vehicles was obstructed by buildings or large vehicles.

The purpose of this test phase was to verify that the integrated VII POC system is capable of supporting Heartbeat message generation and delivery among vehicles. The term "Heartbeat message," refers to the Basic Safety Message defined in Society of SAE J2735. This message has been designed to support a number of anticipated vehicle safety applications, particularly proposed cooperative active safety applications that may be able to prevent or mitigate crashes between vehicles. Since this message standard had not yet been finalized at the time of the VII testing, a version of the message from the then-current draft of SAE J2735 was selected for testing purposes. The over-arching purpose of the Heartbeat Application testing was to verify that the system could deliver this message reliably under various field conditions. The messages were therefore logged as they were transmitted and received, and the main test data that was analyzed consisted of these log files.

4.3.6.1 Heartbeat Service Test Description

Testing was conducted on public roadways under existing field and traffic conditions. Various test cases were run representing different physical roadway and traffic scenarios. These are described within this section.

Test HB-1: Open Road Vehicles Approaching

The goal of this test was to evaluate the basic behavior of Heartbeat message exchange between two approaching vehicles. In this test, two vehicles were driven past each other in opposite directions at 50 mph. The Heartbeat message transmission and reception at each vehicle was logged and the data was subsequently analyzed.

The basic test scenario is depicted in Figure 4-34, and the test course illustrated in Figure 4-35.

Figure 4-34 Test HB-1 Setup

Figure 4-35 Test HB-1 Test Course

Test HB-2: Open Road Vehicles Approaching, with Occluding Truck
The goal of this test was to evaluate the behavior of Heartbeat message exchange between two approaching vehicles in the presence of occluding vehicles (in this case a large truck). As illustrated in Figure 4-36, the two vehicles were driven past each other in opposite directions at 50 mph, and one vehicle was traveling behind the truck. The Heartbeat message transmission and reception at each vehicle was logged and the data was subsequently analyzed. The road segment used for this test was the same as that used in Test HB-1.

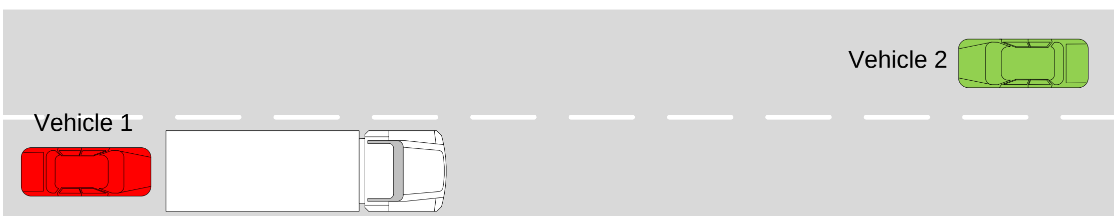


Figure 4-36 Test HB-2 Setup

Test HB-3: Intersection Approach
The goal of this test was to evaluate the behavior of Heartbeat message exchange between two vehicles approaching each other orthogonally (at 90°). This scenario featured an intersection in which the line of sight was blocked by a large building. As illustrated in Figure 4-37, the two vehicles were both in motion and approached the intersection from different directions as shown in the illustration. One vehicle performed a "right turn," and the other proceeded straight through the intersection.

The Heartbeat message transmission from, and reception at, each vehicle was logged and the data were subsequently analyzed.

Figure 4-37 Intersection Approach Test Scenario

Test HB-4: Left Turn with Occluding Truck
The goal of this test was to evaluate the behavior of Heartbeat message exchange between two vehicles approaching each other when one vehicle is hidden (occluded) by a large truck. As illustrated in Figure 4-38, the two vehicles were driven towards an intersection in opposing directions with one vehicle closely following a large truck. The truck and the following vehicle turned left in front of the other approaching vehicle.

The Heartbeat message transmission from, and reception at, each vehicle was logged and the data were subsequently analyzed.

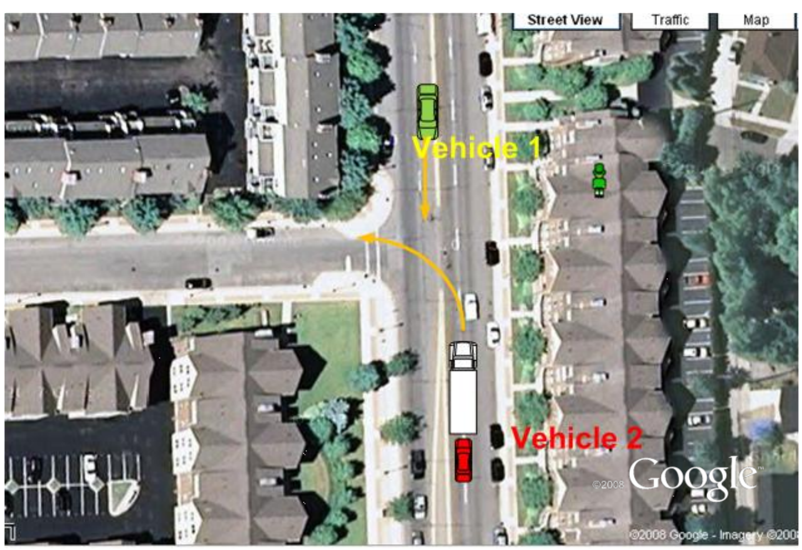


Figure 4-38 Occluded Intersection Test Scenario

Test HB-5: Congested Traffic, No RSE

The objective of this test is to assess the ability to receive Heartbeat messages from multiple vehicles in motion. The test consisted of three vehicles as illustrated in Figure 4-39. One pair of vehicles approached the other vehicle, and all three vehicles exchanged heartbeat messages as they approached, passed and receded.

The Heartbeat message transmission from, and reception at, each vehicle was logged and the data was subsequently analyzed.

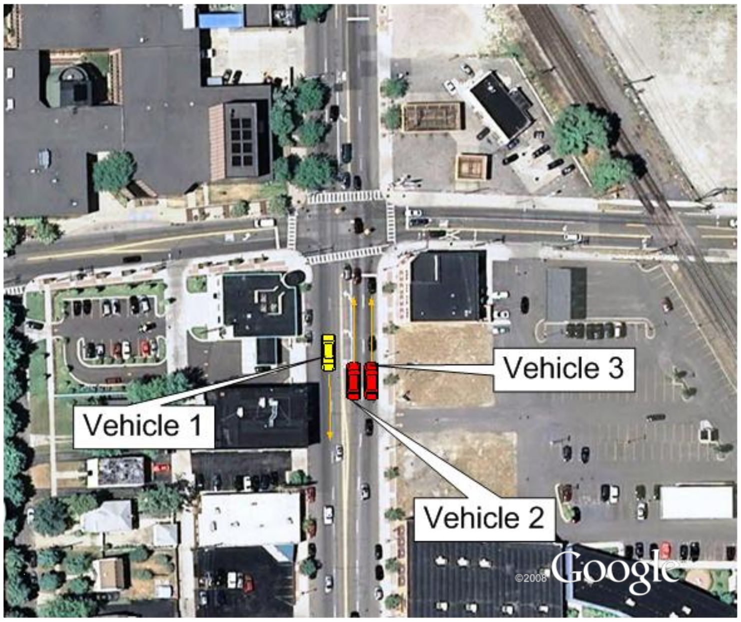


Figure 4-39 Congested Traffic Heartbeat Test Scenario

Test HB-6: Congested Traffic With RSE

This test was a repeat of HB-5, except that the scenario also included an RSE. This added additional message congestion since the RSE was sending WSAs on the CCH. The objective of this test was to show that the WSA and Heartbeat messages (both top priority messages in the system) can co-exist and their simultaneous use does not result in one message type being lost.

The setup for this test was the same as for HB-5, except the RSE was added as shown in Figure 4-40.

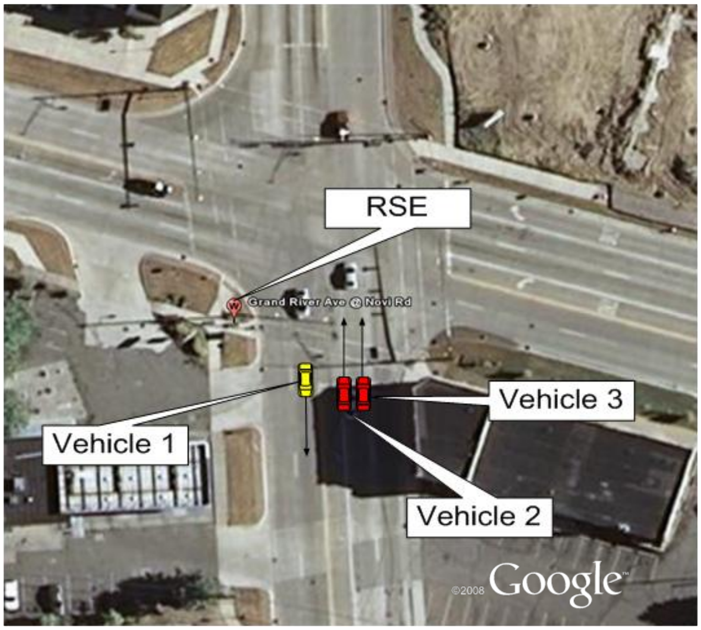


Figure 4-40 Congested Heartbeat with RSE Test Setup

4.3.6.2 Heartbeat Service Test Observations/Results

In general, the Heartbeat tests indicate that the Heartbeat concept is viable.

As shown in Figure 4-41, it appears that we can achieve >99% Heartbeat message reliability within ±50 m range, and >90% reliability within 75 m range, although clearly antenna performance and orientation play a key role in this performance measure. A substantial improvement would result if the recommendations in Section 4.3.1 were implemented. Range at first reception was better than expected (≈180 m open road, no other vehicles).

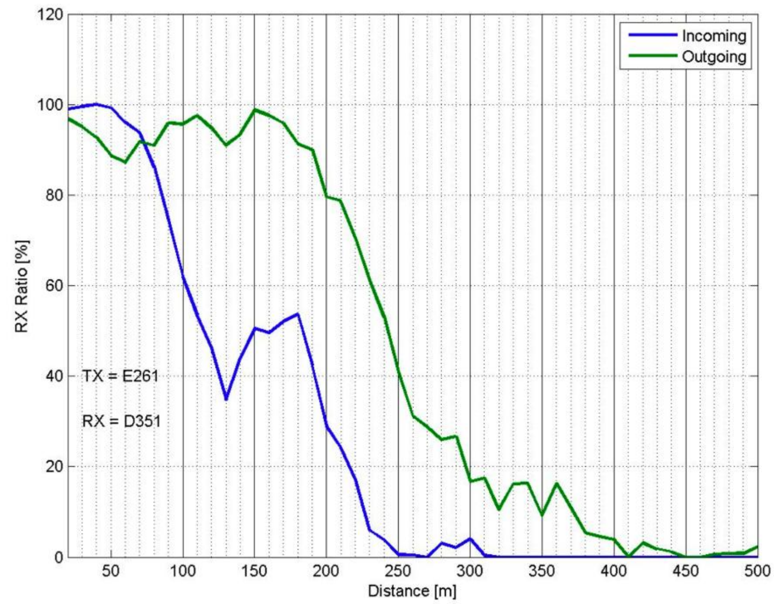


Figure 4-411 Heartbeat Success Ratio vs. Range On Open Road

The presence of other vehicles and roadside effects had variable results. In general, the presence of other vehicles between sending and receiving vehicles reduced the range at which vehicles can first hear each other (from 180 m to about 97 m) , but as can be seen in Figure 4-42, this did not substantially reduce the reliability of the messages at close ranges where the Heartbeat Application performance is especially critical.

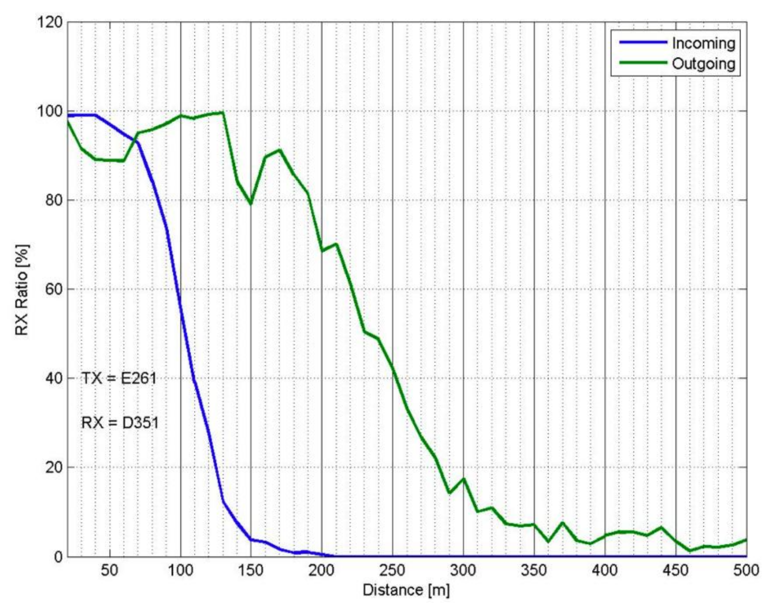


Figure 4-422 Heartbeat Success Ratio vs. Range On Open Road with Occluding Truck

Range for crossing vehicles in an intersection is better than expected (≈60 meters) with occluding buildings. Multipath apparently allows moderate non-line of sight communications. Figure 4-43 shows the specific measured situation where one vehicle stops on a side street away from the intersection, while the other vehicle drives through the intersection.

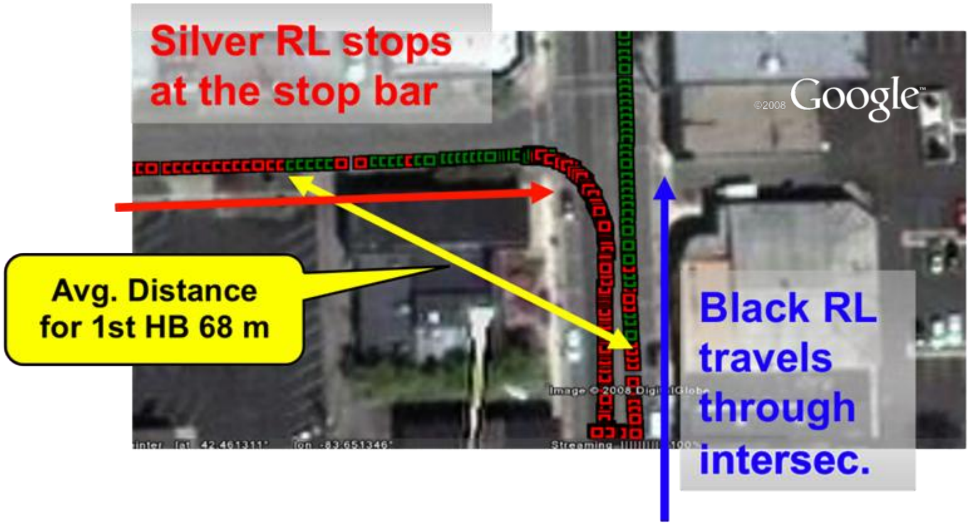


Figure 4-43 Occluding Buildings Heartbeat Test Scenario

As shown in Figures 4-44 and 4-45 below, the overall range performance was significantly degraded in this scenario, compared with line of sight tests, but the system still appears to provide sufficient capability to support useful applications.

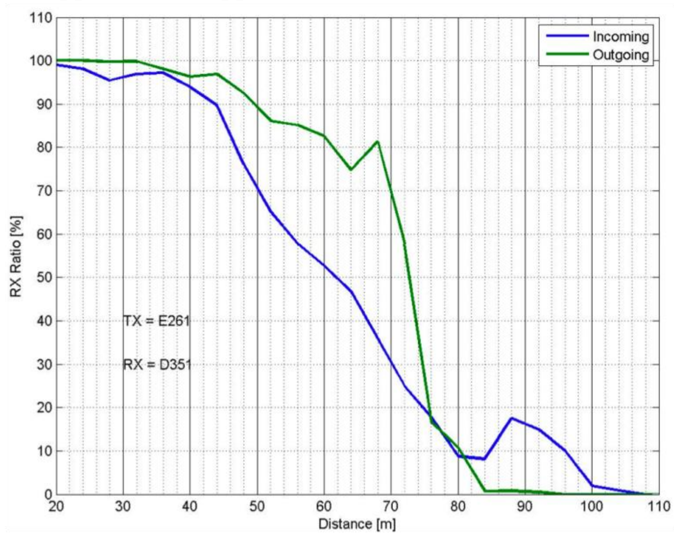


Figure 4-434 Heartbeat Success Ratio vs. Range for Moving Vehicle (Intersection Test)

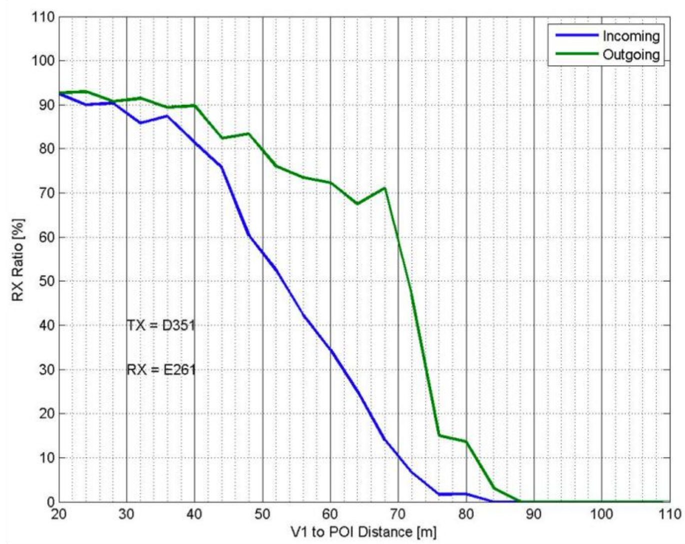


Figure 4-445 Parked Vehicle Heartbeat Success Ratio vs. Range (Intersection Test)

Other observations from the Heartbeat tests include:

- Average distance between vehicles when first Heartbeat received was not significantly different between congested traffic and free-flow traffic.
- Antenna placement (and presumably antenna design) warrant further concentrated research for range optimization.
- Active Safety Applications require near-real-time, deterministic performance of the OBE processing environment.
- Bugs (clock synchronization and GPS outages), and the non-deterministic behavior of OBE functioning noted in heartbeat testing, appear to be POC implementation issues rather than architectural flaws in DSRC or the Heartbeat concept.

4.3.6.3 Heartbeat Test Anomalies

The Heartbeat tests were hampered by a variety of test and system anomalies. While these anomalies make it difficult to assess certain elements of the Heartbeat service behavior, they do not result in a significant error in the overall results. These anomalies are discussed below.

Timing Issues

One of the parameters tested in the Heartbeat tests was the latency of the messages. Since Heart beat messages are supposed to represent the current dynamic state of the vehicle at the time the message is sent, the time delay of the messages is important. The physical flight time of the messages between vehicles is very short (on the order of hundreds of nano-seconds), but if a message is delayed in the sending or receiving processes, the result can be that the user of the message may be acting on data that is no longer relevant. The importance of latency depends on how the messages are used. For example, if the application is a lane change warning system, where the relative distance of the vehicles is small, but their relative separation changes very slowly, latency may not be particularly important. However, in highly dynamic situations, it may be very critical.

The Heartbeat tests attempted to measure this latency with limited success. The problem is that the clocks in the vehicles are not absolutely synchronized, and the logging system used to measure the transmission and reception of the messages is not a high priority process in the OBE. The result is that the time measurements in the OBE logging system vary significantly, and this obscures any actual latency in the message processing. In effect, the system used to measure latency has so much timing irregularity, that it prevents any accurate measure of the Heartbeat service latency by itself. When the effect of time synchronization (or the lack of synchronization) between the vehicles is included, the apparent latency becomes large, but there is no accurate way to determine what the actual Heartbeat system latency is.

Sufficient analysis of this phenomenon was performed to indicate that the Heartbeat service needs to be implemented in a real time software system, and that overall system processing speed is (obviously) critically important for low latency uses of the Heartbeat service. It would seem appropriate to develop and include latency requirements in any future specification of the Heartbeat system.

Out of Order Heartbeat Messages

Related to the latency issue discussed above, it was found that some messages were received out of order. Since the time interval between sent messages is nominally 0.1 seconds, the appearance of out of order messages indicates the presence of significant differential message latencies. Again, since the message latencies are being measured using the OBE logging system(which is itself subject to timing irregularities), it is not certain that sequential messages are actually being processed at different speeds, or if the logging of these messages is simply occurring at different times. There are some indications that, because the OCM handles messages in independent processing threads, it is possible that two sequential messages may be processed at different rates, and ultimately delivered in the reverse order in which they were sent.

Because a user application is unlikely to use the local reception time in the processing of Heartbeat messages, and because the Heartbeat message itself contains the timestamp at which it was generated, it is clear that any user application should be able to easily differentiate such messages, and not erroneously determine that the sending vehicle is moving backwards. As a result the ordering of the messages is not particularly critical. However, as described above, latencies large enough to result in out of order messages may, depending on the application, render a late message unusable. If this were to occur regularly the effect would be an under-sampled measure of the situation of the sending vehicle, and the application performance and reliability would suffer.

Antenna Orientation Variation

During the tests it was observed that Heartbeat message reliability (measured by lost packets versus range) was different for vehicles when they were approaching versus departing. Further examination of this phenomenon indicated that, because of the shape of the test vehicle roof, the antennas on the test vehicles were tilted upwards to the front. Because of the antenna pattern (the sensitivity of the antenna as a function of elevation and azimuth angle) this tilt apparently provided better RF link margin as the vehicles were moving away.

These two situations are compared in Figures 4-46 - 4-49. Figure 4-47 shows the Heartbeat reception rate (Packet Success Rate) with the tilted antenna orientation. Seen in the graphs, the success rate falls off more rapidly with range for vehicles as they approach (blue lines) than when they are departing (green lines). Figure 4-49 shows the same measurements when the antenna orientations have been reset to horizontal. The “knee” of the packet success rate curve is extended by about 20-30 m and the approaching and receding curves are closer together. It is also interesting to note that in all cases, the receding values exhibit longer range at high packet success rates. This is apparently due to differences in the antenna patterns, presumably resulting from the vehicle roof. The antennas are placed on the rear edge of the roof. In the forward direction the antenna has an extended ground plane, while in the rearward direction it does not.

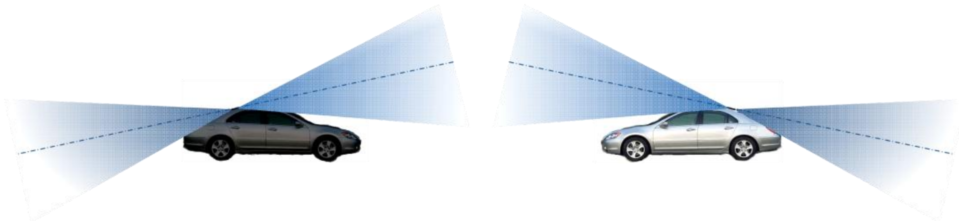


Figure 4-46 Tilted Antenna Orientation

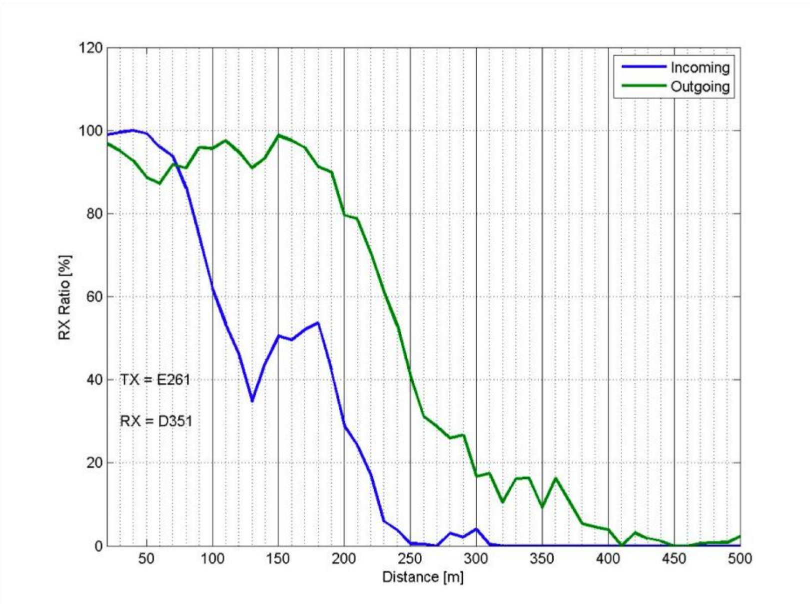


Figure 4-47 Heartbeat Success Ratio With Tilted Antennas

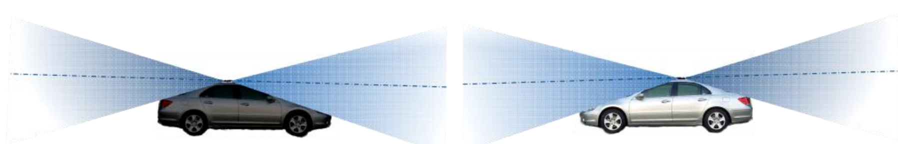


Figure 4-48 Horizontal Antenna Orientation

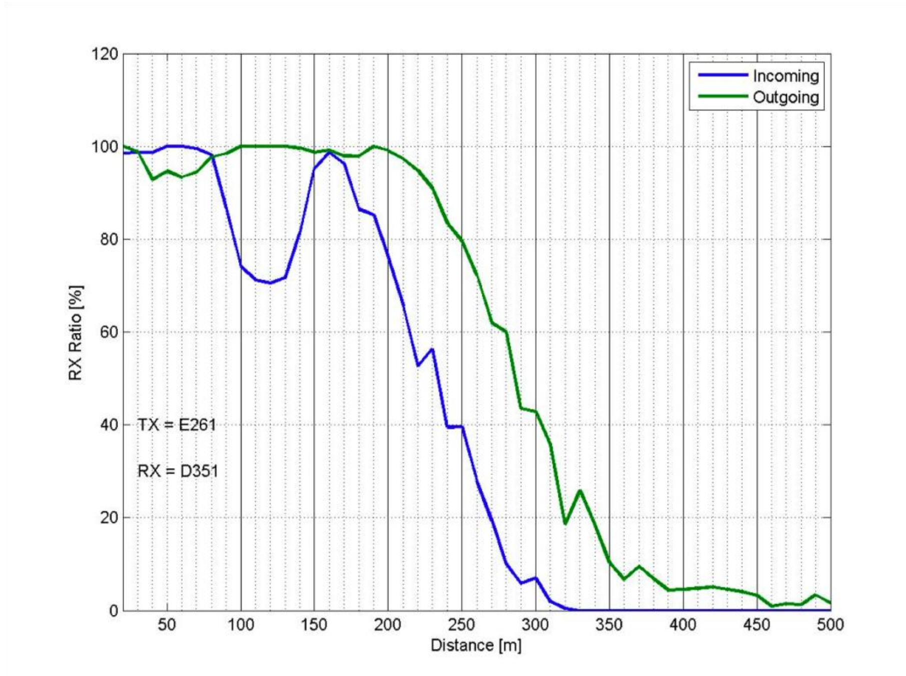


Figure 4-49 Heartbeat Success Ratio With Horizontal Antennas

Since vehicles are found in a wide variety of shapes and sizes, it is not realistic to assume that any two vehicles sharing Heartbeat messages a will have perfect antenna orientations. As a result, it is clear that a vehicle deployment should include requirements on radiated power in azimuth and elevation (for the transmit side), and on receive sensitivity in azimuth and elevation (for the receive side). Careful development of these requirements should assure that vehicles transmit signals that other vehicles can optimally receive, regardless of their size and particular physical structure.

4.3.7 Network Enablers Service

The Network Enablers service was designed to assess the viability of two related concepts in the VII system:

- The ability to use conventional web services techniques to deliver services to clients far removed from the service and separated by both the VII network system and the intermittent connectivity of the DSRC link as the vehicle moves through the network.
- The ability to support data exchanges that, either because of file size or transaction complexity, extend beyond the time that a vehicle is in range of a single RSE.

The system was implemented, as described in Volume 2a. The Off-Board Navigation Application (OBNA) uses a navigation service located at Navteq in the Chicago, IL area. This was tied in to a Transaction Services Manager (TSM) located at the Herndon, VA facility. A traffic service was also tied into the TSM, thus forming a suite of services linked via the TSM.

4.3.7.1 Network Enablers Test Setup

Test of the system involved two different activities. In one set of tests, different navigation routes were requested, and the vehicle was driven along those routes. Based on changes in the traffic situation provided to the navigation service by the traffic service, the route was changed. As the vehicle passed an RSE, the route was updated to reflect the changed route. This demonstrated the utility of the web services concept applied in the VII system.

In the second test, routes of various lengths were requested and the vehicle was driven out of the RSE coverage zone. As the route length increased, the time required for the service provider to compute the route and send the result increased. In longer route cases, the vehicle would leave the RSE coverage zone before the route response was fully received. As the OBE arrived at the next RSE, the service would resume and the remaining route information would be delivered. This tested the ability of the system to support services over multiple RSEs. These tests were carried out as described below.

Test OBN-1 Short Route:
In this test, a short route (typically only a few miles) was requested while the vehicle was stationary at an RSE. As soon as the route request was activated in the vehicle, the vehicle began moving away from the RSE as quickly as possible.

The time required to complete the request and response cycle was recorded, and the completeness of the route information was checked.

Test OBN-2 Medium Route:
In this test, a medium length route (typically about 500 miles) was requested while the vehicle was stationary at an RSE. As soon as the route request was activated in the vehicle, the vehicle began moving away from the RSE as quickly as possible.

The time required to complete the request and response cycle was recorded, and the completeness of the route information was checked.

Test OBN-3 Long Route:
In this test a long route (typically about 2500 miles) was requested while the vehicle was stationary at an RSE. As soon as the route request was activated in the vehicle, the vehicle began moving away from the RSE as quickly as possible.

The time required to complete the request and response cycle was recorded, and the completeness of the route information was checked.

The test setup for all three tests is illustrated in Figure 4-50. Each test was run several times, with tests originating alternately from RSE A and RSE B.

Figure 4-50 Off-Board Navigation Test Setup

The routes were requested at an RSE, and the vehicle moved away from the RSE as soon as the request was made.

4.3.7.2 Network Enablers Test Results and Findings

For the short route, 12 out of 14 requests were served correctly. The two failed requests were attributed to a dropped link in the wireless TSM control. The TSM was being controlled by a technician in the vehicle using a laptop and a wireless modem over a commercial 3G data service. The coverage for the 3G service was poor and the connection was lost, so the TSM shut down. Normally, in a full-scale deployment, the TSM would be controlled by an Enterprise Network Operations Center (ENOC) or by the service provider.

The average response time for the short route was 12.8 seconds with a standard deviation of 2.8 seconds. In all cases, the short route request and response were completed before the vehicle left the RSE wireless coverage area. The resulting turn-by-turn route list contained about 1.5 pages (screens) of directions.

For the medium route, nine out of ten requests were served correctly. The failed request was attributed to a dropped link in the wireless TSM control, the same issue as described above.

The average response time for the medium route was 41.1 seconds with a standard deviation of 4.8 seconds. In all cases the medium route request and response were completed before the vehicle left the RSE wireless coverage area. The resulting turn-by-turn route list contained about four pages of directions. One additional run was made wherein the vehicle was set slightly farther from the RSE at the time the request was made, and then driven quickly away. The vehicle escaped the RSE zone before the response was completed, and the response completed when the vehicle arrived in the zone of the next RSE. While only anecdotal, this indicates that a route of about 500 miles and four pages of turn-by-turn directions appears to be the approximate upper bound for service fulfillment at a single RSE using the POC implementation of Off-Board Navigation.

For the long route, nine out of ten requests were served correctly. The failed request was a result of an OBE fault (the OBE had to be restarted).

The average response time for the long route was 1.2 minutes, although this period is primarily determined by the drive time between RSEs, so the exact value and variation is not meaningful.

In all cases, the long route response was not completed before the vehicle left the RSE wireless coverage area. The vehicle traveled the distance to the next RSE, and resumed the download of the response data. The resulting turn-by-turn route list contained about seven pages of directions. Observation of the data streaming indicated that the download/connectivity behavior of the system was slightly different when beginning at RSE A and completing at RSE B versus starting at RSE B and completing at RSE A. This is attributed to the fact that RSE A was located on a slight rise in the road, so the vehicle had good line of sight for a long distance. The communications stream always ceased at the same general place where the road took a dip downward. Similarly, RSE B was located in a slight depression, and there was substantial tree foliage obscuring the radio path. As a result, RSE B had less range. These differences did not affect the ability of the system to perform as expected.

In none of the three test cases did the system fail to deliver the data at the next RSE if the request was sent at the first RSE.

The ability of the Network Service Enabler system to support handoff of services between RSEs is an important accomplishment, since it substantially increases the range of services that can be offered over the VII system. It effectively reduces the impact of intermittent connectivity (due to incomplete RSE coverage). The result is that, even with significant gaps in geographic coverage, the VII system is able to effectively serve most applications (those not requiring streaming data such as voice or video).

4.4 VIIC Applications Results and Findings

The applications developed for the POC are described in detail in Volume 2a. This section describes key findings related to the applications that are not considered system services. Specifically, these included Off-Board Navigation, Electronic toll and Parking payments, and a specialized test of safety communications using Signal Phase and Timing (SPAT) messages from a traffic signal controller.

4.4.1 Off-board Navigation Results and Findings

The OBNA was tested as part of the Network Service Enablers system service test described in Section 4.3.7.

During this test several routes were requested. A short route (<2 miles), a medium route (≈500 miles) and a long route (>2000 miles). With the exception of a few situations where a test system data link failed (this was a commercial 3G link used to observe and control part of the system backend, it is not actually part of the VII system), the system reliably responded to route requests and delivered route directions either at the same RSE as the request, or at the next RSE encountered following a request.

Figures 4-51 and 4-52 show a typical cross-country route delivered during the Network Service Enablers tests.

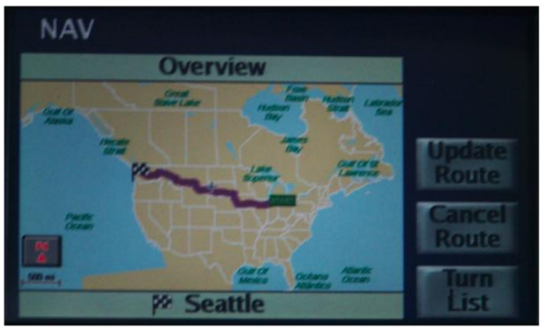


Figure 4-51 Long Route Map

Figure 4-52 Long Route Directions

4.4.2 Electronic Payment – Tolling Results and Findings

The Electronic Toll Payments Application was tested in two separate locations. The first test was carried out at the junction of the I-96 freeway and Novi Road (a major arterial road) in the DTE. The second test was performed in Northern California at the Dumbarton Bridge Toll plaza located on the east-bound lanes of California Highway 84.

As described in Volume 2a, a “plaza zone” is used to activate the Tolling Application, and specific “payment zones” to execute the toll payment transactions.

4.4.2.1 DTE Tolling Test Overview

The DTE Toll Plaza zone, shown in Figure 4-53, encompasses the interchange including all of the exit and entrance ramps (shaded green). Ten Toll Collection zones (shaded yellow and labeled in the figure) are located as specific regions of roadway within the Toll Plaza.

During the tests the vehicles, were driven through the site on a course that passed through all of the collection zones at least once. The tests consisted of multiple passes through or near the plaza zone. Some passes were specifically intended to activate payments in specific zones, while others were intended to test the ability of the system to differentiate when to pay and when not to pay. These tests included passes on nearby side roads that are close but not inside the toll plaza where no toll was to be paid, and also passes that entered, exited and then re-entered payment zones to test the ability of the system to resist accidentally paying the toll twice.

Figure 4-53 Toll Plaza Region for Tolling Application Test

Figure 4-54 below shows (red lines) a composite of all of the passes through the DTE tolling test site accumulated during the trial. The yellow circle near the center of the interchange is the location of the RSE.

Figure 4-54 Cumulative Vehicle Passes During Tolling Tests

4.4.2.2 DTE Tolling Test Results

The overall performance of the system in executing the Tolling application was excellent.

In general, the system was able to differentiate toll payment zones properly, and was able to execute transactions when it was supposed to. In addition, the system was fast enough to execute these transactions properly while the vehicle passed through the zones at freeway speeds.

Test Anomalies

During the test, two of the toll payment zones were incorrectly configured. One was setup as a nonpayment zone, and the other had the wrong directionality. As a result, the tests involving these zones resulted in different behavior than expected in the test plan. Examination of the logs, however, indicates that, for the configurations in place at the time of the test, the system behaved exactly as was intended.

The results of the DTE Electronic Toll Payment tests are summarized in Table 10.

Test Objective	Test Results
Test A: Differentiation of payment and non-payment situations • Eastbound on I-96 at posted speed limit with vehicle in the right lane. • Vehicle should enter the plaza zone, then zone 7 without paying a toll, and then exit the plaza.	Successful: • The vehicle traveled the entire span of the plaza in the right eastbound lane of I-96. • System indicated entry of the plaza; and zone 7, and properly ignored zone 7, • System indicated plaza exit. • No toll collection, as expected.
Test B: Differentiation of payment and non-payment situations • Westbound on I-96 at posted speed limit, in the right lane. • Vehicle should enter the plaza zone, then enter zone 7 without paying a toll, then the vehicles should enter zone 1, pay a toll and then exit the plaza zone.	Successful: • The vehicle traveled the entire span of the plaza in the right westbound lane of I-96. • System indicated entry of the plaza, and zone 7. • Vehicle properly ignored zone 7. • System indicated entry of zone 1 and vehicle properly paid the toll.
Test C: Toll Payment • Eastbound on I-96 to Novi Rd exit, then south to Crescent Blvd. • Both vehicles should enter the plaza zone, then enter zone 8 with both vehicles paying a toll in the same order that they entered the zone, and then exit the plaza.	Successful: • The vehicle traveled the expected path through the plaza. • System indicated entry of the plaza and zone 8. • Vehicle properly started the toll payment process. • The transaction was completed before the vehicle left the plaza.

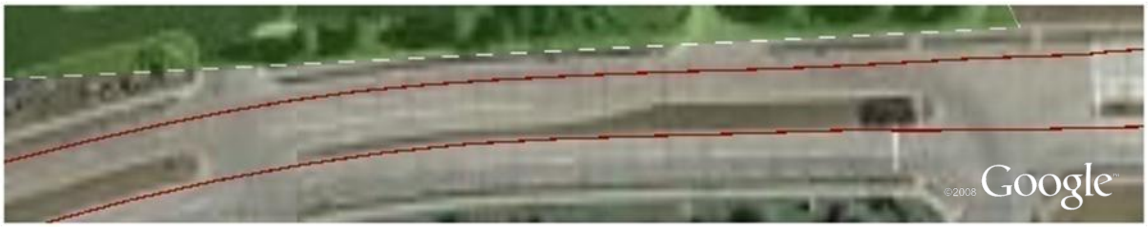
<table>
<tr>
<td>Test D: Differentiation of Payment and Non-Payment Situations
• East and westbound on Crescent Blvd.
• Vehicle should receive the toll WSA’s and WSMP messages but should not enter the plaza.</td>
<td>Successful:
• The vehicle made the pass without indicating that it entered the plaza.</td>
</tr>
<tr>
<td colspan="2">The plaza geometry and vehicle path for Test D are shown in Figure 4-55 below.


Figure 4-55 Test Setup for Plaza Zone Differentiation</td>
</tr>
<tr>
<td>Test E: Multiple Zone Encounters
• Northbound on Novi Rd to westbound I-96.
• Vehicle should enter the plaza, then enter zone 7 and pay a toll.
• Vehicle then exits the plaza, and reenter the plaza, then zone 7 without paying the toll.
• Vehicle then enters zone 1 without paying a toll, and then exits the plaza.</td>
<td>Successful:
• System indicated entry of the plaza, and zone 7.
• Vehicle paid a toll.
• System indicated exit and reentry of the plaza.
• System indicated exit and reentry of zone 7.
• Vehicle properly ignored zone 7 (toll already paid).
• System indicated entry of zone 1.
• Vehicle properly paid a toll before exiting the plaza.</td>
</tr>
<tr>
<td colspan="2">The plaza geometry and vehicle path for Test E are shown in Figure 4-56 below.


Figure 4-56 Test Setup For Plaza Exit and Reentry Test</td>
</tr>
</table>

Test F: Sequential Toll Payments • Westbound on I-96 to Novi Rd exit and then reenter I-96 westbound after a pause. • Vehicle should enter the plaza, then enter zone 10, pay a toll, and then exit the plaza before momentarily reentering the plaza. • Vehicle should then enter zone 9, pay another toll, and then exit the plaza again.	Successful: • System indicated entry of the plaza, and zone 10. • Vehicle paid a toll. • System indicated plaza exit and then a short time later indicated plaza re-entry and entry of zone 9. • Vehicle paid another toll.
Test G: Multiple Zone Encounters (timed) • Eastbound on I-96 to Novi Rd exit then north to 12 Oaks Drive. • Vehicle should enter the plaza, then enter zone 8, pay a toll, and then exit the plaza before momentarily reentering the plaza. • Vehicle then enters zone 7 and pays a toll again only if enough time has elapsed since paying the toll in zone 8.	Successful: • System indicated entry of plaza and zone 8. • Vehicle paid a toll. • System indicated plaza exit, and reentry within time limit. • System indicated entry of zone 7. • Vehicle paid a toll and exited the plaza.
Test H: Differentiation Of Zones with Close Passes • Southbound on Novi Rd to Fountain Walk Ave to Sheraton Dr. • Vehicle should enter and exit the plaza without paying a toll.	Successful: • System indicated entry of plaza • Vehicle passed close to Zone 9, but system did not indicate entry of zone 9. • System indicated plaza exit.

The plaza geometry and vehicle path for Test H are shown in Figure 4-57 below.

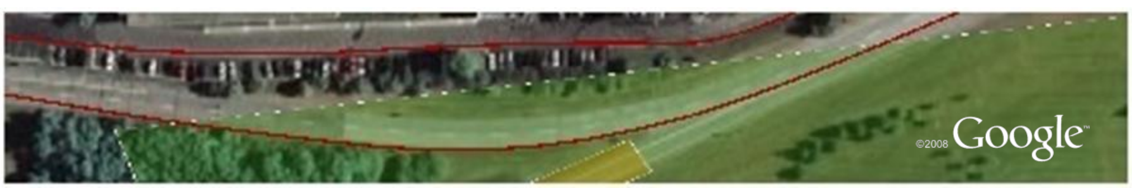


Figure 4-57 Close Approach Test Setup

Test H: Multiple Zone Encounters • Southbound on Novi Rd to eastbound I-96. Vehicle should enter the plaza, then enter zone 7 without paying a toll. • Vehicle then enters zone 5, and pays a toll. • Vehicle then enters zone 7 again without paying a toll, and then exits the plaza.	Successful: • System indicated entry of the plaza, and zone 7. • Vehicle did not pay a toll. • System indicated entry of zone 5. • Vehicle paid a toll. • System indicated reentry of zone 7. • Vehicle properly ignored zone 7 (toll already paid).

Table 9 Electronic Toll Payments DTE Test Results

4.4.2.3 California Toll Test Overview

Figure 4-58 shows the POC test electronic toll plaza and collection zones overlaid on the conventional toll collection facility at the Dumbarton bridge entry area on California Highway 84. This roadway is not limited access, but the pedestrian and bike traffic is isolated from the motor vehicle traffic by a concrete barrier. While speed through the toll plaza is limited to about 20 mph, speeds on the roadway either side of the plaza are typically higher.

Figure 4-58 Dumbarton Bridge Toll Plaza Setup

In the figure above, the vehicles enter the electronic plaza zone as they pass through the conventional toll gates (bridge over the roadway). This facility is equipped with the FasTrak Electronic Toll Collection system, so properly equipped vehicles typically pass through the toll gates at about 20 mph. Once in the plaza zone, the vehicle sets up a session with the Toll Payment Application in the Local Transaction Processor (LTP) attached to the RSE (located in the region of the red pin in the figure), and when it enters the collection zone, the vehicle system sends a message to the LTP Application indicating that it has entered the collection zone. The LTP Application then sends a payment invoice that is to be signed by the vehicle system and returned for payment.

4.4.2.4 California Toll Test Results

The test results are shown in Figure 4-59. This figure represents seven passes through the plaza as indicated by the red path lines. The location where the first indication of the toll plaza is received is denoted by "1st WSMP". This represents the point where the vehicle system first becomes aware of the toll plaza. The entry to the plaza zone is denoted "Entry". This is the location where the vehicle system identifies itself to the tolling system and informs it that it has entered the plaza zone. The toll system responds with an acknowledgement including an invoice for the toll (based on the vehicle type). When the vehicle enters the collection zone, it then responds by sending the signed invoice back to the LTP. This location is denoted "Collect" in the figure. The LTP then finalizes the transaction by sending an executed copy of the invoice for the vehicle's records. This location is designated as "Invoice" in the figure. Each type of location identified in the figure also includes the number of the run it is associated with.

The first two runs passed through the plaza in the upper left region which is a toll plaza parking area. This allowed low speed test of the system and facilitated configuration and debugging without the need for the vehicle to drive over the entire bridge.

Figure 4-59 Dumbarton Bridge Toll Test Results

The third through seventh runs passed through the plaza zone on the main road at full road speed (40-60 mph).

In general, the tests were successful. Toll information was passed to the vehicle, and the vehicle responded properly based on its location relative to the plaza and payment zones. There was one run that was not successful. This is described in the following section.

4.4.2.5 Tolling Test Anomalies

An unexpected system behavior was observed during the Dumbarton tolling tests. As can be seen in Figure 4-59, at the location of the "Invoice 6" balloon, there is a gantry that crosses the east-bound traffic lanes. This gantry houses equipment used for enforcement of the FastTrak tolling system. The gantry is composed of a large steel tube structure supporting a variety of cameras and electronic equipment. During numerous runs, it was observed that the DSRC Radio link was lost as vehicle passed under the gantry. The link was typically re-established once the vehicles moved far enough past the gantry that the line of sight to the RSE did not pass through the gantry (the road curves slightly, making this geometry possible). Tolling runs where the invoice was received prior to the vehicle passing beyond the gantry were typically successful, while those under or past the gantry were typically not successful. This phenomenon deserves further examination, but it appears that the structure of the metal gantry causes a re-scattering of the DSRC signal that results in enhanced multipath fading in this region, and this effectively cancels the radio signal for a large region beyond the gantry. This behavior has implications for the design and layout of the toll zones and may also impose some operational constraints on the system.

4.4.3 Electronic Payment – Parking Results and Findings

The Electronic Parking Payments tests were carried out at a parking lot in northern Illinois (adjacent to one of the POC Systems Engineering team facilities).

The operation of the Electronic Parking Payment Application is similar to the Electronic Toll Payment Application. The vehicle enters a payment plaza zone and obtains collection zone in formation. When the vehicle enters the collection zone, the payment process is executed. In the POC Parking Payment Application, the parking was a fixed fee event-based type of charge, as opposed to a parking rate with a times parking duration.

4.4.3.1 Electronic Parking Payment Test Overview

The test facility is shown in Figure 4-60. In the figure, the dark blue region is the Parking Plaza zone, and the red region is the Parking Payment zone. This setup is intended to simulate a confined entry region typical of most pay parking facilities. The RSE is located next to the building on the right side of the blue plaza region.

Figure 4-60 Electronic Parking Payment Test Setup

The surrounding trees and other buildings give an approximate coverage pattern shown shaded in green in Figure 4-61 below (the figure has been rotated 90° counter clockwise from Figure 4-62 for clarity). The test cycle was designed so that vehicles traveling south on Lake Street would receive the parking lot announcements well in advance of the entrance to the parking lot on the north end of the building.

Figure 4-61 Parking Payments RSE Coverage

4.4.3.2 Electronic Parking Payment Test Results

The results of the Electronic Parking Payments tests are summarized in Table 11. These tests were performed using two OBEs operating in a single vehicle.

Test Description	Test Results
Test A:Parking Zone Discrimination • The driver enables the parking application and selects a payment account before starting the pass. • Vehicle travels southbound on Lake Street past the parking lot, and then northbound on Lake Street past the parking lot. • The vehicle OBEs should receive the service announcement and display appropriate information from the announcement on the HMI. • No invoices should be issued by the LTP, no transactions should occur.	Successful on four different runs, two southbound, two northbound: • Parking application turned on using the HMI on both units. • The second payment account available was selected on both units. • Lot definitions received on both units. • HMI presentation made on both units. • Transaction record cleared, no invoice, no transaction on both units.
Test B: **Parking Announcement Discrimination** • The driver disables the parking application before starting the pass. • Vehicle travels southbound on Lake Street past the parking lot, and then northbound on Lake Street past the parking lot. • The vehicle OBE's should receive the service announcement and not display any parking information on the HMI. • No invoices should be issued by the LTP, no transactions should occur.	Successful on four different runs, two southbound, two northbound: • RSE encountered, no parking-related activity on both units.
Test C: Non-Parking Event • The driver enables the parking application and selects a payment account before starting the pass. • Vehicle travels southbound on Lake Street, enters the parking lot, enters the entrance zone, and then leaves. • The vehicle OBE should receive the announcement, display information about the parking lot, and then display information about the potential transaction. • The LTP should issue invoices but no transactions should occur.	Successful on two different runs: • Two passes were made in and out of the lot without paying. • The application was able to keep track of all of the invoices and messages and route them to the proper OBE. • All messages sent by either the OBE or LTP were received according to the logs. • No charges to either OBE were recorded.

Test D: Parking Transaction • The driver enables the parking application and selects a payment account before starting the pass. • Vehicle travels southbound on Lake Street, enters the lot, enters the entrance zone, confirms the transaction, parks temporarily (without turning off the engine), and then leaves the lot. • The lot inventory should be adjusted and complete transactions should occur.	Successful on two different runs: • Two passes were made into the lot. • Payment was selected. • All invoices were paid by the Network User Payment Service (NUPS) and the application was able to keep track of the details of the two transactions occurring nearly simultaneously.
Test E: Parking Transaction with Change In Payment Method • The driver enables the parking application and selects a payment account before starting the pass. • Vehicle travels southbound on Lake Street, enters the lot, enters the entrance zone, changes the payment account, confirms the transaction, parks temporarily (without turning off the engine), and then leaves the lot. • The lot inventory should be adjusted and completed transactions should be charged to the correct account.	Nominally successful on two runs: Two passes were made into the lot. • Two of the four attempted transactions were successful with the invoice charged to the account selected in the payment zone. • Two transactions did not complete because of positioning service difficulties or operator error.
Test F: Partial Transaction Recording • The driver enables the parking application and selects a payment account before starting the pass. • Vehicle travels southbound on Lake Street, enters the lot, enters the entrance zone, changes the payment account, confirms the transaction, parks with the engine off, and then leaves the lot. • The lot inventory should be adjusted. • The OBE should remember the details of the incomplete transactions while the engine is off, and complete transactions should occur.	Nominally successful on two different runs: • 2 passes were made into the lot with the vehicle turned off each time. • All of the transactions completed to the point where the invoices were paid and the signed receipts were delivered to the LTP. • The vehicle was able to retain knowledge of the state of the transactions in all cases.

Table 10 Parking Test Results Summary

4.4.4 Safety Link Testing

A test of the communication link between an RSE located at an intersection and an OBE-equipped vehicle was designed and conducted in order to assess the impact of increased volume of message traffic on the reception of messages being broadcast from an RSE. This test was intended to determine if DSRC was capable of providing reliable communications for safety applications, in this case as exemplified by a traffic signal message, and to determine the impact of DSRC message congestion on high priority safety messages.

4.4.4.1 Safety Link Test Overview

The test consisted of positioning ten OBE equipped vehicles in proximity of the intersection and having them transmit Heartbeat messages at increasing rates to simulate increased control channel message traffic.

An RSE was connected to a traffic signal controller and was set up to generate and transmit a SPAT message on the control channel. This message was sent once during each control channel interval. A test vehicle was equipped with an application that received, logged, and displayed the results of the SPAT message on the OBE display.

As the stationary OBEs were transmitting the Heartbeat messages, the test vehicle was driven from a long distance away through the intersection. The combined SPAT and Heartbeat messages were received and logged.

Four tests were conducted in all with each test including approach and departure of the intersection in two different directions. For each of the four tests the Heartbeat transmission rate was increased to simulate increased DSRC message traffic. The objective was to measure the impact that this increasing message density had on the successful transmission and reception of the SPAT messages. The Heartbeat rates used in the test were: zero (no interfering heartbeat messages), 10 heartbeat messages per second 20 Heartbeat messages per second then 50 Heartbeat messages per second.

The tests were conducted at the intersection of 9 Mile Road and Meadowbrook Road, the site of RSE# 688. This site is illustrated in Figure 4-62.

Figure 4-452 Safety Message Test Setup

The intersection consists of eight approaches with four through lanes and four dedicated left turn lanes controlled by a single Siemens Eagle Mod52 traffic signal controller. There is no separate traffic signal for separately controlling the left turn lanes.

4.4.4.2 Safety Link Test Results

The tests showed that SPAT messages could reliably be received from 300 to 500 m from the intersection (depending on the local terrain, buildings, etc), with increasing reliability as the distance to the intersection declined (an expected result). At nominal vehicle approach speeds of up to 30 mph, these ranges indicate that the vehicle can receive safety messages between 15 and 30 seconds before it arrives at the intersection (depending on speed and the local terrain).

Table 12 below shows the SPAT reliability metric (the total percentage received versus sent as measured from the first received message to the last received message. This metric includes the result of losing the message at long distances at the start and end of each run, so it is not an indication of the near field reliability, but it is a measure of the overall message reception capability.

Test Run	Heartbeat Interference Rate	SPAT Reliability Metric (Southbound)	SPAT Reliability Metric (Northbound)
1	Zero (no interference)	65%	72%
2	10 per Sec	66%	71%
3	20 Per Sec	61%	50%
4	50 Per Sec	60%	55%

Table 11 Safety Communications Reliability vs. Interference Level

The impact of interference can be seen in the table by comparing the reliability metrics at different interference levels. Clearly, the presence of interfering message traffic reduces the overall reception reliability (the metrics decrease with increasing heartbeat interference rates. However, it is interesting to note that the impact of higher rates is not linear. As the interfering rate increases it appears to have a relatively finite impact on reliability regardless of the actual rate. For example, the reliability changes by only 1 percent as the interference rate increases from 20 per second to 50 per second. In the case of the northbound runs, the reliability actually increases, indicating that the reliability is more sensitive to other factors such as surrounding traffic and terrain, than to interference rate.

Further examination of the test setup indicates that the impact of interference is presumably greatest at long ranges. During the test, the test car was also emitting heartbeat messages. In this situation is it likely that the RSE issuing the SPAT messages may not hear the heartbeat messages from the test car (the hidden terminal effect) and this may result in the message collision avoidance mechanisms used by DSRC to fail. This is especially likely because the RSE and the test car will, in the absence of any known interferers, send their messages at the start of the Control Channel interval, so, if they cannot hear each other, there is a virtual certainty that they will interfere. The result is a larger percentage of messages lost from collisions at long ranges (where the signals are weak), again not an unexpected result. Since SPAT messages are sent at a fixed rate (not dependent on the rate of heartbeats), and since the test car is traveling at nominally the same approach speed for each of the tests, the time the vehicle is in the weakest reception area (where the message collisions occur) is the same, regardless of the interference rate. As a result, we would expect to see the number of missed SPAT messages to be fairly constant even if the interference rate is changing, and this is generally what is seen in Table 12. The presence of interference has a finite impact, and the rate of interference (the congestion in the channel) has little measurable impact.

What this ultimately means is that the safety link tests confirm that DSRC is effective for high priority safety communications, and it is not significantly impacted (especially inside reasonable ranges where the message collision avoidance processes are functioning) by the volume of message traffic, at least at the levels of message traffic tested here.

4.4.4.3 Safety Link test Anomalies

The only anomaly observed during this test was the reception of SPAT and heartbeat messages out of order. This was not the purpose of this test, and it did not have any impact on the test results. As described elsewhere in this report, the out of order messages appear to be a result of CPU loading and thread management in the OBE software.

5 VII POC Program Recommendations

The section below outlines high-level observations regarding core elements of the systems, and recommendations. The recommendations are covered in more detail in the Volume 1a. However it is important to note that further work is needed to investigate the issues described below in order to arrive at satisfactory solutions prior to any large scale implementation. Happily solutions to most of the issues noted have well understood technical solution. The results of the findings of this study and any work stemming from the study should be used to update the standards.

5.1 Communications

In general, the VII POC Communications system met the basic requirements. However, the POC tests identified a number of shortcomings in the DSRC standards that need to be addressed. Most of these relate to the dynamic nature of the users in the roadway environment. It appears that the fact that the transmitters and receivers are in motion relative to each other was not adequately considered in the specification of the protocols, nor was the effects of priorities and the effects of channel synchronization fully anticipated. These limitations were apparent in nearly all of the POC application tests. Specific recommended refinements to the standards are:

- The IEEE P1609.3 standard and the resulting radio implementations need to be refined to include measures of signal quality and reliability prior to indicating that a service is available. This avoids problems associate with a user joining a service that is too distant to be used reliably.
- The service decision logic defined in IEEE P1609.3 needs to be improved. Specifically, the current standard does not adequately support arbitration between multiple services available from multiple providers. In the original standards it was assumed that RSEs (providers) would be far apart, and there would be no opportunity for multiple providers to compete, but this does not appear to be a sound assumption. The range of DSRC is longer than expected, and it is reasonable to assume that RSEs will be in range of one another.
- The IEEE P1609.3 standard provides some application state related input to the service decision process, but this is insufficient to support more complex application operations. The state definitions need to include the ability for applications to decline services, to suppress service notifications, to query available services, and possibly to allow multiple user applications to "vote" in order to more effectively arbitrate between competing services and user applications. For example, if the advisory/signage application has already received the signs being broadcast on the service channel, there is no reason to continue to re-join the service channel and receive the signs again. To avoid this requires some mechanism for the

application to be notified of the services being offered along with an indicator of the specific version, time or other identifier of the content to be provided by the service (for example a sign sequence number). If the content is not new to the user application, then it would decline the service and another application might be able to use a different service.

- The CSMA windows used to avoid interference need to be optimized to account for synchronism caused by the control channel /service channel interval. Currently the CSMA process only allows for seven possible back-off interval choices. When there are many users trying to send messages on the CCH, this results in many collisions because many users choose the same back-off time. If the number of back-off choices were increased, then there would be more choices and fewer overall collisions.
- The overall message priority scheme needs to be re-thought. Message priorities are used in different places for different purposes, and these are not always consistent. For example a transmit message queue should always follow a strict priority scheme, but a service decision should not. The reason is that an outgoing message has a fixed priority, but an incoming message (or a service that will provide an incoming message) does not. The priority of an incoming message depends entirely on whether that message is new to the user application (see above discussion of joining based on new content). If the service content has already been received, then receiving it again offers no value to the user application, so the local (to the OBE) priority of that message is zero. The priority scheme needs to be extended to address these different types of priorities and to address the issue that some priorities depend on the context of the OBE application (i.e., the "local" context) rather than on some global priority.

5.2 Positioning

Positioning functionality is required by user terminals in order to provide accurate state information (e.g., speed at a given location), so the system requirements need to impose some basic accuracy requirements on user devices in order to assure that data provided to the system or to other users is valid. However, the specific means by which this position determination is carried out should not be prescribed. This is especially important since some low cost terminals may not be able to include a GPS positioning system for economic reasons.

The positioning requirements must be significantly refined and extended to account for observed variations under static and dynamic conditions, and to align the positioning accuracy with the types of expected interoperable applications.

While the system should not prescribe a particular positioning solution, it is apparent that significant development work needs to be performed in order to improve positioning accuracy, and to assure accurate position availability under all expected operational situations. This work should address improvements in GPS solutions, but it should also include non-GPS schemes, multiple sensor systems (data fusion), and low cost relative positioning methods.

5.3 Network Enablers

The Network Enablers functionality is composed of two parts. First is the function that allows users to migrate from one RSE to another while maintaining a service session. Second, is the web services back end that allows multiple services to be combined easily and efficiently. The POC demonstrated that the web services approach is compatible with the dynamic vehicle environment where intermittent and somewhat short connectivity sessions are the norm. However, these systems are heavily dependent on the choices of the service providers, and, other than providing the knowledge that they are compatible with the system, no additional development work is required.

The session migration capability requires further consideration. In the original system requirements and system architecture, this capability was considered to be external to the system. This decision was primarily due to the need for protecting the privacy of users as they move a service session from one RSE to another. This is still a concern, but the POC experience also indicates that this is a capability that the system must provide. To not include it in the VII network means that it will be implemented in different ways by different providers and this will significantly complicate both the terminals and the data traffic.

As a result, it is recommended that the functionality associated with migrating service sessions between RSEs should be included in the system requirements as a system function, but that it also be required that such a function not be capable of being used to track a user. Such a competing set of requirements will also require additional security development work to create a scheme that operates as part of the system, but cannot be used by the system operators or their agents to track users.

5.4 Security

The security system is a large parallel subsystem that was implemented in a bare bones fashion in the POC program. The POC program demonstrated that the basic security functions can be implemented and they work in the context of the system. However only a small amount of work was done to analyze the threats and to understand how to identify and mitigate attacks. In addition, while an anonymous signing system was demonstrated, no work was done to demonstrate how such anonymous signatures can represent assurance that the terminal has not been altered in some way. The system implemented for the POC has known issues related to management of large-scale attacks. Work done on the POC indicates that the current concept can be refined to address these issues, but the detailed analysis and subsequent development work remains to be performed.

It is recommended that the anonymous signing scheme be further analyzed, simulated and refined to assure that the anonymous signatures are meaningful (that they certify the legitimacy of the terminal); this work should include development of a secure software provisioning system. The message signing and verification strategy used for high rate messages such as Heartbeats should be revisited and simulated to arrive at an optimal blend of security and system throughput. In addition the work begun on the POC program to identify and mitigate attacks should be further extended and developed into an overall security management definition. Finally, the security implementations should be further refined and optimized and then the entire security system should be tested by third parties to assess its strength.

5.5 Advisory Message Delivery Services

The AMDS and associated OBE Signage application performed well in the POC. The POC used simple geographic regions to activate signs, but the definition of these regions in the current concept of operations is complex, and it is not clear if this is the best way to manage activation of messages. In addition, the system is slightly unstable in terms of when messages actually appear at RSEs, and how persistent they are. The system operates well enough to demonstrate the concept, but it could be improved and made easier to use and more robust.

It is recommended that the system be refined to improve how priorities should be interpreted in the context of other user activities (for example, should the message be displayed in the current circumstances). The activation criteria (when is a message relevant?) need to be significantly refined, and the overall management of the system in terms of properly setting configuration parameters and defining advisory message delivery parameters must be automated so that erroneous combinations cannot occur.

5.6 Probe Data Service

The probe data service was shown to work during the POC, but the concept is not particularly refined. It is not clear as yet that collecting this volume of data from all vehicles is necessary (under most conditions messages sent from vehicles on the same roadway are heavily redundant), and the rules developed to maintain user privacy and non-tractability are very complex. During POC it was found that the slightly unreliable nature of radio communications coupled with the privacy rules imposed on the Probe Data system resulted in significant loss of data. It is likely that many of the Communications Services improvements described above will alleviate some of the problems experienced in the POC Probe Application, but since it represents a significant privacy and performance element of the system, the conceptual basis for the Probe System also needs to be refined and better understood.

It is recommended that the probe data collected in the POC be analyzed and that representative models of probe data user applications be developed in order to assess the true mathematically relevant requirements on vehicle sampling density and scope of vehicle parameters sampled. This may include new concepts such as linking heartbeat messages with the probe system to optimize the sampling of the roadway environment while minimizing the total volume of data collected. The privacy rules associated with PDC need to be more fully integrated into the data collection strategy in order to better understand and control when PDC is and is not appropriate, and how this works given the existence of intermittent and not always reliable radio communications. In addition the system data throughput and subscriber capacity needs to be assessed.

5.7 Probe Data Management

While the tests of the Probe Data Management system were slightly ambiguous, the testing did result in a heightened awareness of the use of the application. It appears that the PDM concept needs to be more fully defined. Specifically the current PDM concept does not account for multiple PDM sources (i.e. directives from multiple requesters), and does not provide any mechanism for either coordinating conflicting PDM directives (from different requesters). In addition there is no time-out for PDM directives, so once a vehicle has been directed to a particular probe data schedule, it will continue that schedule indefinitely until it is re-directed by another PDM. This is likely to result in more probe management messages because a reduction in, for example, data collection rate in one area will result in an under sampling in another less congested area. Without some means for defining either geographic limits to the directives, or some mechanism for central control of these directives, the PDM system could create significant variability and possibly even instability in the overall probe collection environment. These issues are presumably easily addressed, but as yet they have not been modeled and no controls of default processes have been defined.

It is recommended that a detailed system definition effort be performed to define these default mechanisms and to determine how the system addresses multiple directives.

5.8 Heartbeat Service

The various heartbeat tests performed in the course of the program indicated that the system is prone to a variety of timing anomalies. In some cases these were due to application issues that resulted in excessive CPU usage, and in other cases the issues seemed to be related to the use of multiple parallel application execution threads (for example out of order heartbeat messages). Regardless of the source of these timing anomalies, it is unlikely that any system will ever provide “real time” heartbeat messages. Out of sequence sending of Heartbeat messages is simply an especially egregious case of timing.

The heartbeat message is intended to provide raw data that a user application can use to develop situational awareness. However, the validity of this awareness is a direct function of the accuracy and validity of the received data.

While it is important when developing situational awareness to have timely data, it is more important that the data be valid. A message received a few tens of milliseconds after it was generated isn’t necessarily useless. However, a message that has internal inconsistencies in the data it carries can lead to an erroneous awareness of the current situation. Currently the Heartbeat message definitions include no requirements on timeliness, nor do they include requirements on the temporal relationship between the various parameters contained in the message. For example, the message contains a time stamp that should be used by a receiving application to put the data in the message in the proper temporal context (e.g. place the car at the right place at the time the message was sent). However, it is clear from the POC tests that the position used in the message may be generated before or after the vehicle speed (for example), and that both of these parameters may be generated well before the application determines the message time to put into the message payload. If these values are skewed significantly in time, then the inherent errors in position determination are amplified, and the overall quality of the situational measurement will suffer.

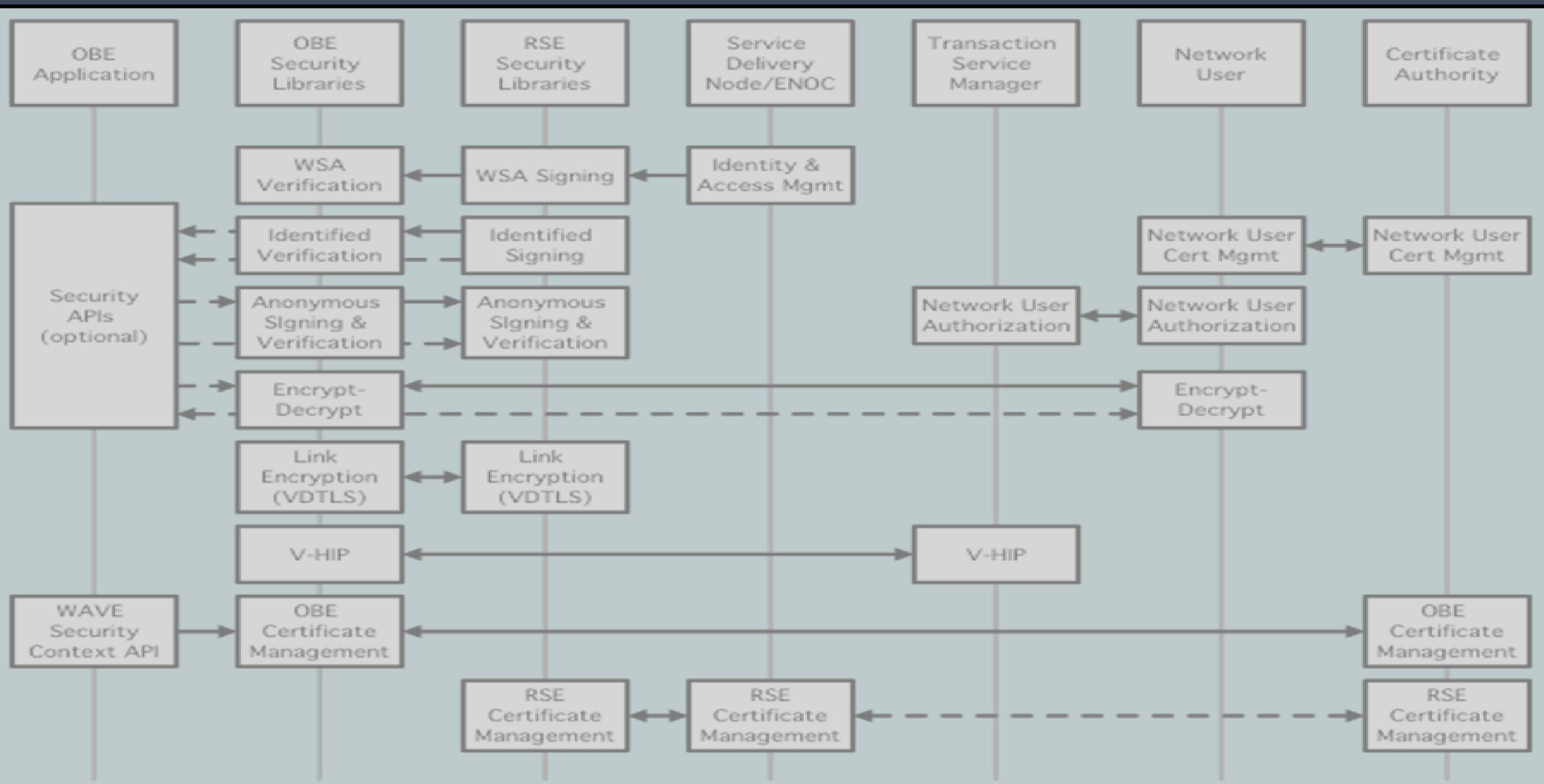
As a result it is essential that the heartbeat message be further refined from a systems perspective, and that this refinement include requirements on overall message latency as well as timing skew between the data elements in the message .

5.9 System Operations Management

The POC system and the system described by the National System Requirements provide a bare bones approach for network users to interact with the system. Essentially, the Information Lookup Service provides a mechanism for a user to query the system and identify which RSEs to use to make services or messages available in the system. This is an effective way to use the system, but it is very inefficient. For example, it is likely that many private network users (private service providers) will not care specifically which RSEs their services are provided from (the more the better), and it is equally likely that road management organizations will care about roads and intersections much more than about RSE identifiers. Clearly the system as currently configured is usable, but it seems reasonable that simpler more intuitive and more relevant interfaces should be available for service and data providers. This could be left to each road authority to develop independently, but since the basic needs of these users are quite similar it seems that this system element could be improved to the benefit of all users.

In addition, the system has numerous configuration parameters at numerous points, and these parameters must all be properly configured for the system to operate properly. During the POC, wrong configuration of these parameters resulted in unstable and unusable operation. Once configured properly the system works well, but as one user pointed out “getting all of the stars aligned properly” is not always a straightforward process.

It is recommended that the overall system operations be more fully automated and that the acceptable combinations of configurations be defined so that improper combinations cannot occur. In addition, the network management interfaces need to be improved to allow efficient and accurate setup of system elements, and to allow operators to accurately see the operational state of the system at any moment.



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